

Advances in modeling energy, water, and land processes and their interactions

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MIT Joint Program On the Science and Policy of Global Change

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MIT Joint Program on the Science and Policy of Global Change

Vision and Overview



We explore the interplay between our global environment, economy, and other human activities, to discover the key processes & interactions and provide a better science basis for decision-making in the public & private sectors.

Our Goals:

Perform & objectively assess uncertainty in economic and environmental projections through probabilistic assessments

Critically and quantitatively analyze environmental management and policy proposals

Consider multiple global change concerns: Food & Water, Energy, Population & Development. Land and Ocean Ecosystems, Earth System Science, Climate Change & Policy

Understand and model complex connections among climate, air pollution, food, water, energy, urbanization, economic development...



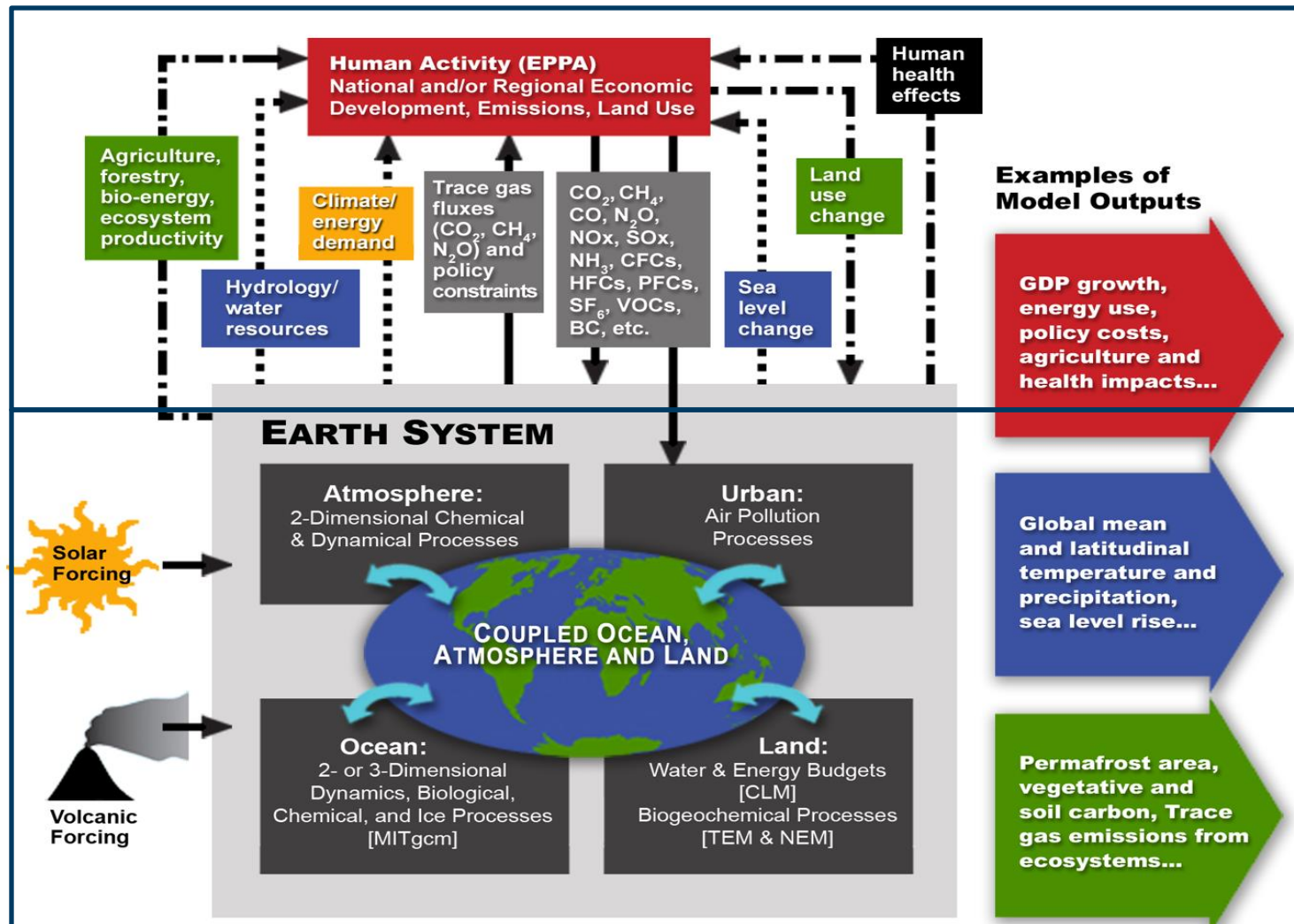
Broader issues in analysis of evolution of energy, water, land systems and their interaction

- Linkages among complex water, energy, land systems
 - Earth system: Insolation (energy) drives the hydrological cycle (water), with runoff (land surface) into rivers/reservoirs, and lakes to determine spatial availability/flow of freshwater.
 - Human system: Water withdrawals for multiple uses, e.g. power plant cooling (energy), irrigation (agriculture and land use), and domestic and industry uses—supply conflicts and water quality effects.
- Modeling issues
 - Scale (Temporal and spatial)
 - Active feedbacks or altered boundary conditions
 - Explicit modeling of processes or reduced form relationships
 - Stocks and flows (GHG emissions—concentrations, river flows-reservoirs—groundwater, depletable energy—renewable/storage)
- Predictability
 - Description of range of outcomes,
 - Quantified as probability
- Adaptation
 - What by whom—national/international level policy and planning or specific investments (public/private, companies/individuals)
 - A problem of investment under uncertainty

MIT INTEGRATED GLOBAL SYSTEM MODEL (IGSM): a tool for investigating linkages among complex human and natural systems—convergence of social science, physical and biological sciences and engineering concepts

Economic
Projection
and Policy
Analysis
(EPPA)
model

MIT Earth
System
Model
(MESM)

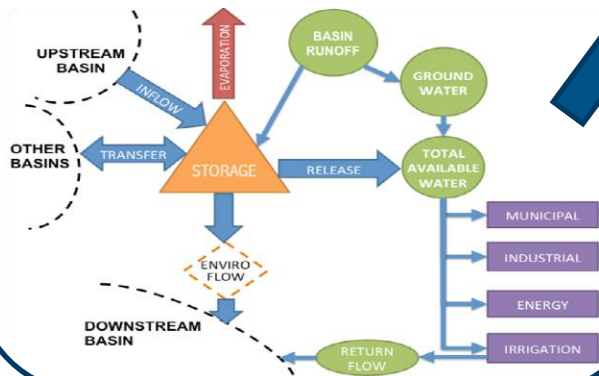
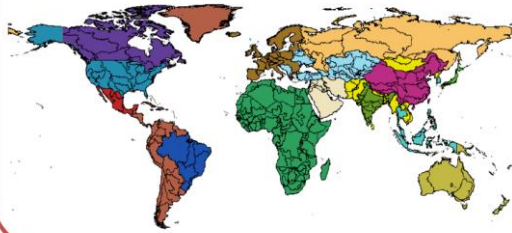


MESM: Sokolov et al. (2017), Manuscript Joint Program. EPPA: Gurgel, (2016): in Vol 3. The WSPC Reference on Natural Resources and Environmental Policy in the Era of Global Change; Chen, et al. (2016): *Economic Modelling*, **52(Part B)**: 867–883. Available at: <https://globalchange.mit.edu/research/research-tools/global-framework>

<http://globalchange.mit.edu/>



ELABORATED IGSM FRAMEWORK

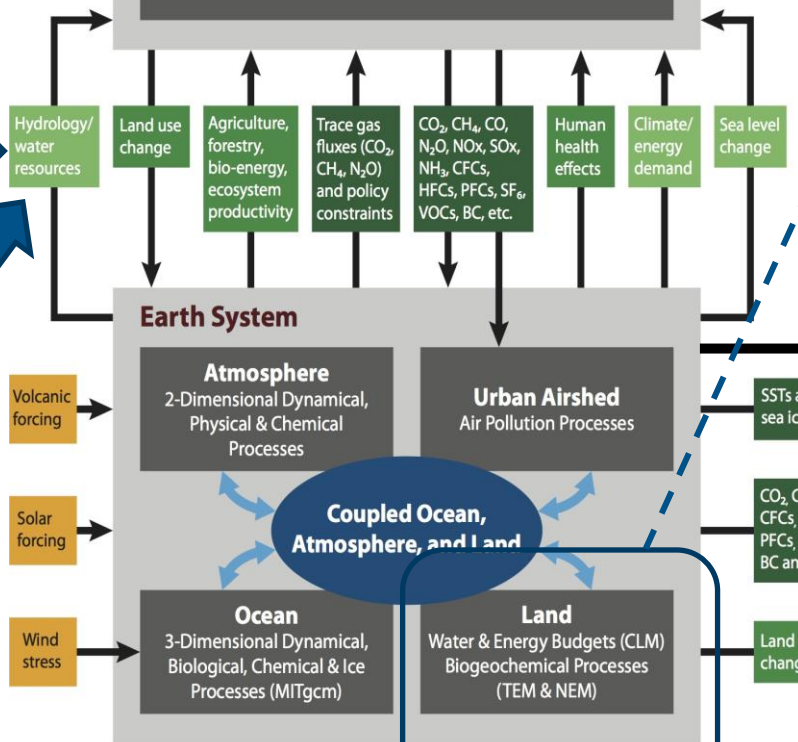


IGSM-WRS: Strzepek, K., C. A. Schlosser, A. Gueneau, X. Gao, C. Fant, E. Blanc, and B. Rasheed, and H. Jacoby (JAMES, 2013).

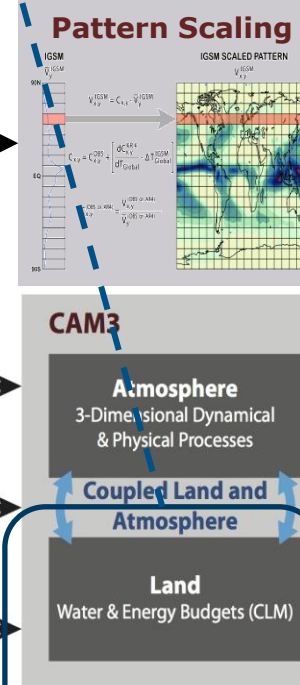


Evaluation and Policy Analysis (EPPA)

for Regional Economic Development,
Emissions & Land Use



Energy-water-land in the earth system



PROJECT RISKS TO THE NATURAL, MANAGED AND BUILT ENVIRONMENTS FROM HUMAN AND NATURAL FORCES AND THEIR CHANGES. ASSESS MITIGATION AND ADAPTIVE ACTIONS.

MODELING WATER MANAGEMENT OPTIMIZATION AND FLEXIBILITY OF FRAMEWORK

Priorities for Release of Supply

- Environmental Baseflow
- Municipal
- Industrial
- Energy
- Agriculture/Irrigation

WATER STRESS INDEX (WSI) [UNITLESS]

- MEASUREMENT OF SYSTEM/ENVIRONMENT STRESS

$$WSI = \frac{\text{Withdrawal (Dom, Ind, Irr)}}{\text{Supply (Runoff, Inflow)}}$$

UNMET DEMAND (UD) [FRACTION OR %]

- INDICATOR OF THE DIRECT HUMAN IMPACT

$$UD = 1 - \frac{\text{Total Consumption}}{\text{Total Demand}}$$

Optimization Algorithm for Each Basin

WATER STRESS INDEX (WSI) [UNITLESS]
 • MEASUREMENT OF SYSTEM/ENVIRONMENT STRESS
 $WSI = \frac{\text{Withdrawal (Dom, Ind, Irr)}}{\text{Supply (Runoff, Inflow)}}$
UNMET DEMAND (UD) [FRACTION OR %]
 • INDICATOR OF THE DIRECT HUMAN IMPACT
 $UD = 1 - \frac{\text{Total Consumption}}{\text{Total Demand}}$

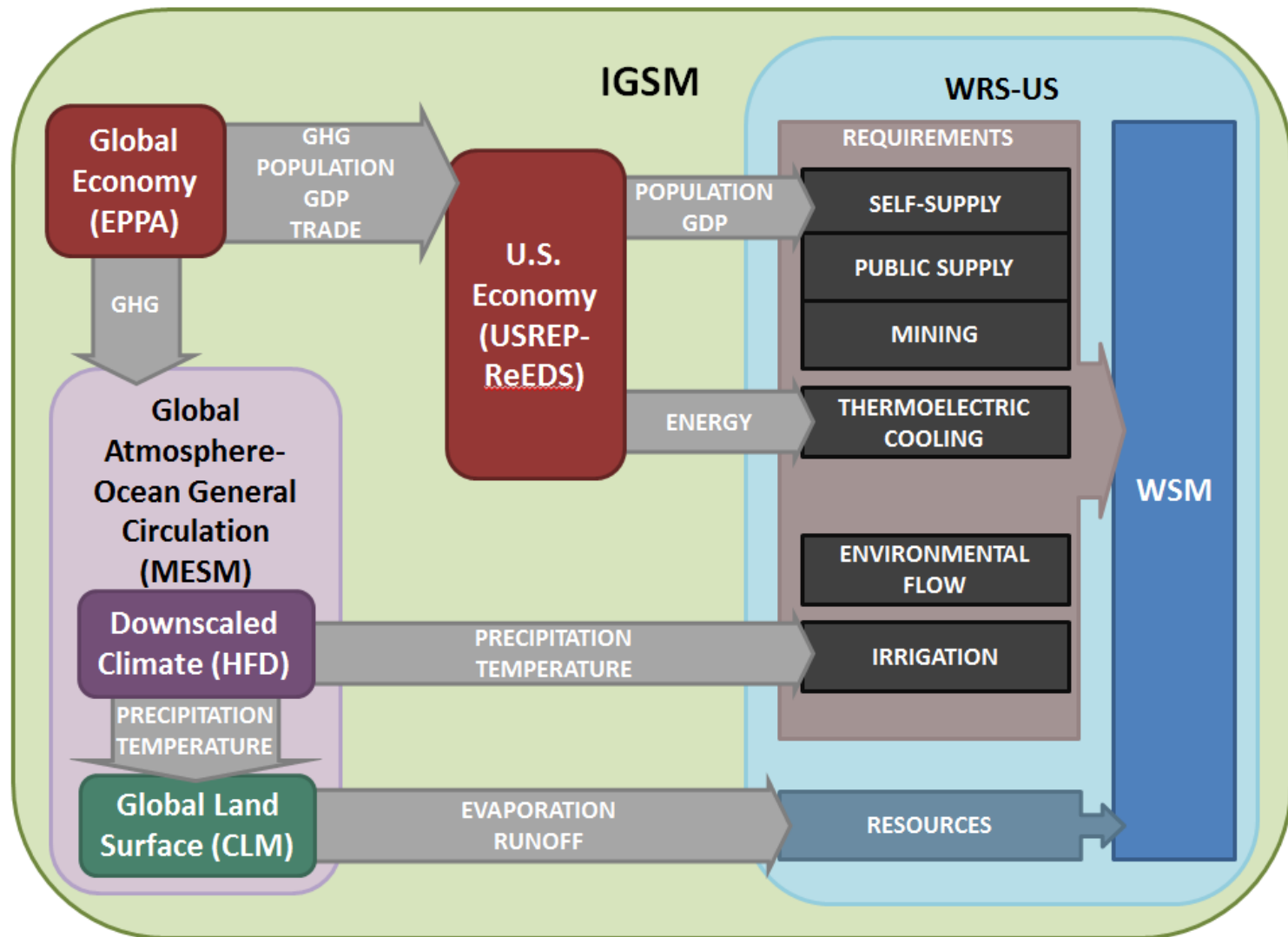


$$OBJ = \frac{SRR_{min}}{12} + \min(SRR) - \frac{SPILL_{min}}{STC} - \frac{ST_{end-yr}}{STC} - 100(\min(ST - EVAP, 0))$$

Qualitatively: Basin Objective

- Maintain highest supply-to-requirement ratio
- Minimal amount of release
- Keep end of year storage high
- High penalty for depleting storage

A Water Resource System model for the US



Make use of variable resolution with links to global forces (i.e. boundary conditions)

Advantages:

Global simulations of MIT IGSM represents updated BAU impacts of stabilization scenarios as energy and environmental policy changes globally.

Multiple runs/large ensembles (100's to 1000's of members) feasible with variation in behavior of multiple GCMS through pattern mapping.

Compare with off the shelf archived GCM runs with fixed concentration paths and inconsistent global economic environment and unable to fully characterize risk space.

Disadvantages:

Effects in the US/North America do not feedback on the globe

Similar detail for the rest of the world would like affect boundary conditions of climate, concentrations, and global trade.

livestock

USREP-ReEDs Coverage

- Flexible aggregation of 50 US states + 16 international regions
- Flexible aggregation of 52 sectors of the economy
- Coal, gas, oil, nuclear, hydro, solar and wind electricity generation.
- Solves in 2- or 5-year time steps to 2050
- 9 household types based on income



USREP-ReEDs Data sources

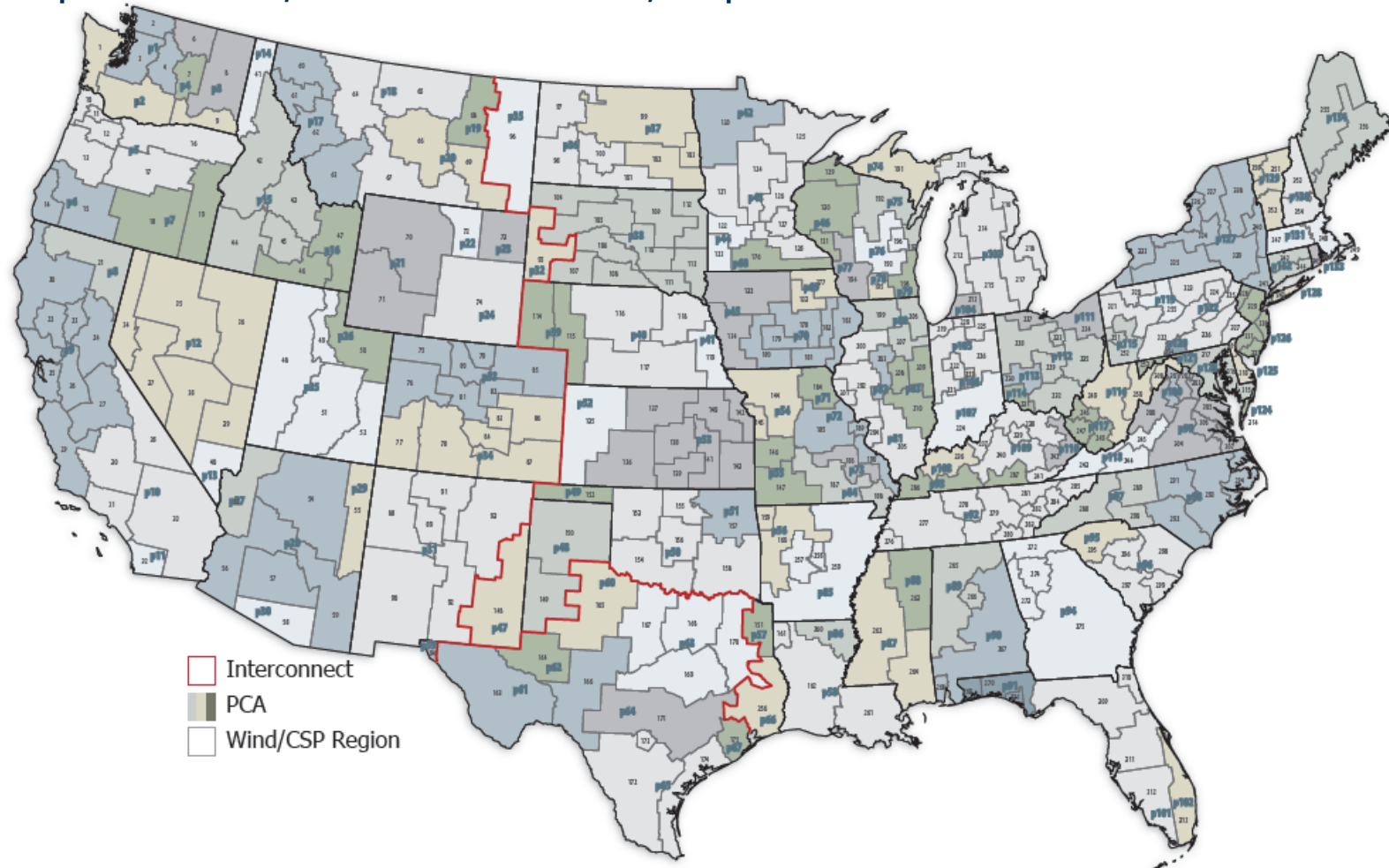
<i>What ?</i>	<i>Where ?</i>	<i>Source</i>
Input/output matrices	US states	IMPLAN (2008): BEA and National Income and Product Accounts (NIPA)
	International	Global Trade Analysis Project (GTAP, 2008), Version 7
Final demand	US states	IMPLAN (2008): NIPA and Consumer Expenditure Survey (CES)
	International	GTAP7
Physical energy flows and prices	US states	State Energy Data System (SEDS), EIA (2009)
	International	IEA/GTAP
Bilateral trade	Between states	Commodity Flow Survey (Lindall et al., 2006)
	Between states and countries	Origin of Movement (OM) and State of Destination (SD), US Census Bureau (2010)
	Between countries	GTAP7
	Electricity	National Renewable Laboratory's ReEDS model
GDP and CO₂ emissions	US states	EIA Annual energy outlook 2015



ReEDS Resolution

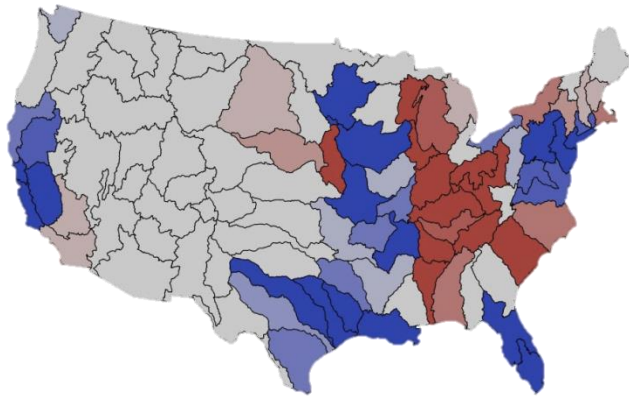
(In progress-linkage of ReEDS Canada and Mexico with North America REP)

Chooses least cost electricity deployment with detailed specification of renewable resources with policy constraints or options—minimum renewable requirements, carbon taxation, cap and trade

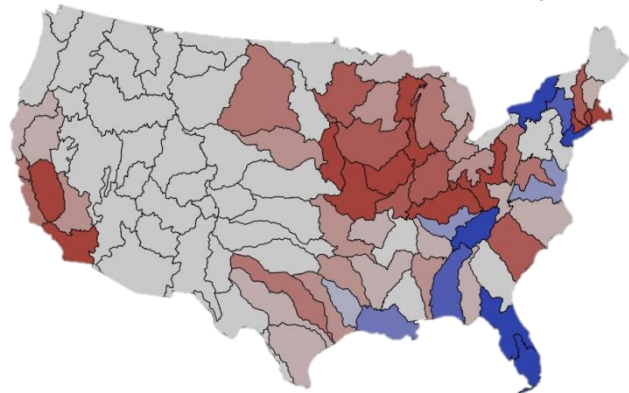


An application: In a stabilization scenario (L1S), increase in renewable deployment significantly reduces power plant cooling water withdrawals, lessening water stress compared with LICE

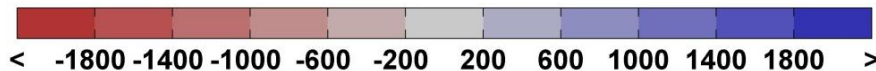
Unconstrained Emission (UCE)



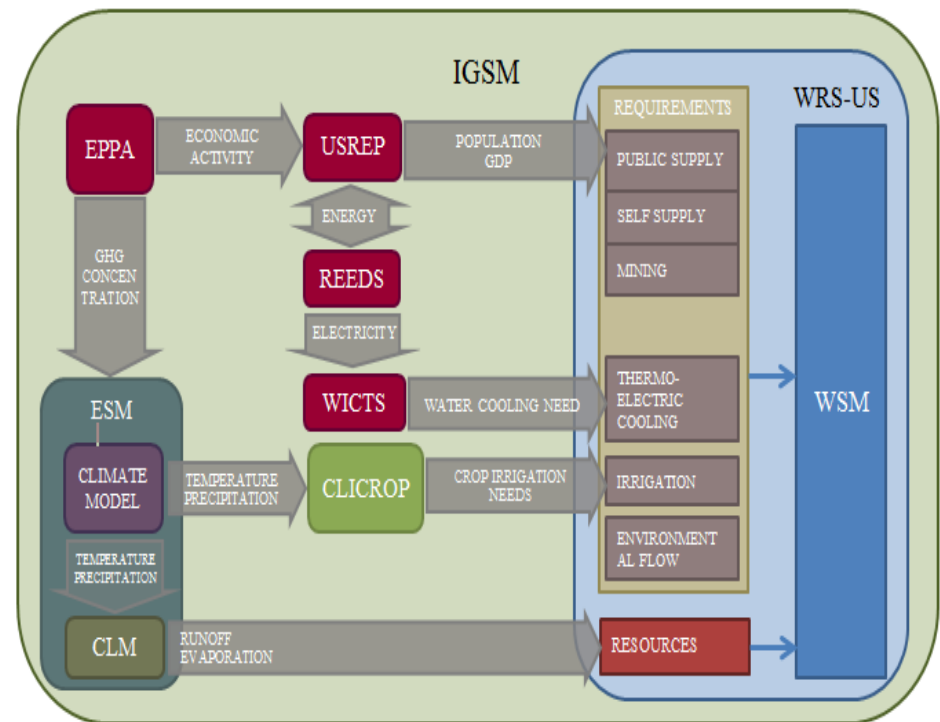
Level 1 Stabilization (L1S)



Change in Cooling Withdrawal (Mgal/day)



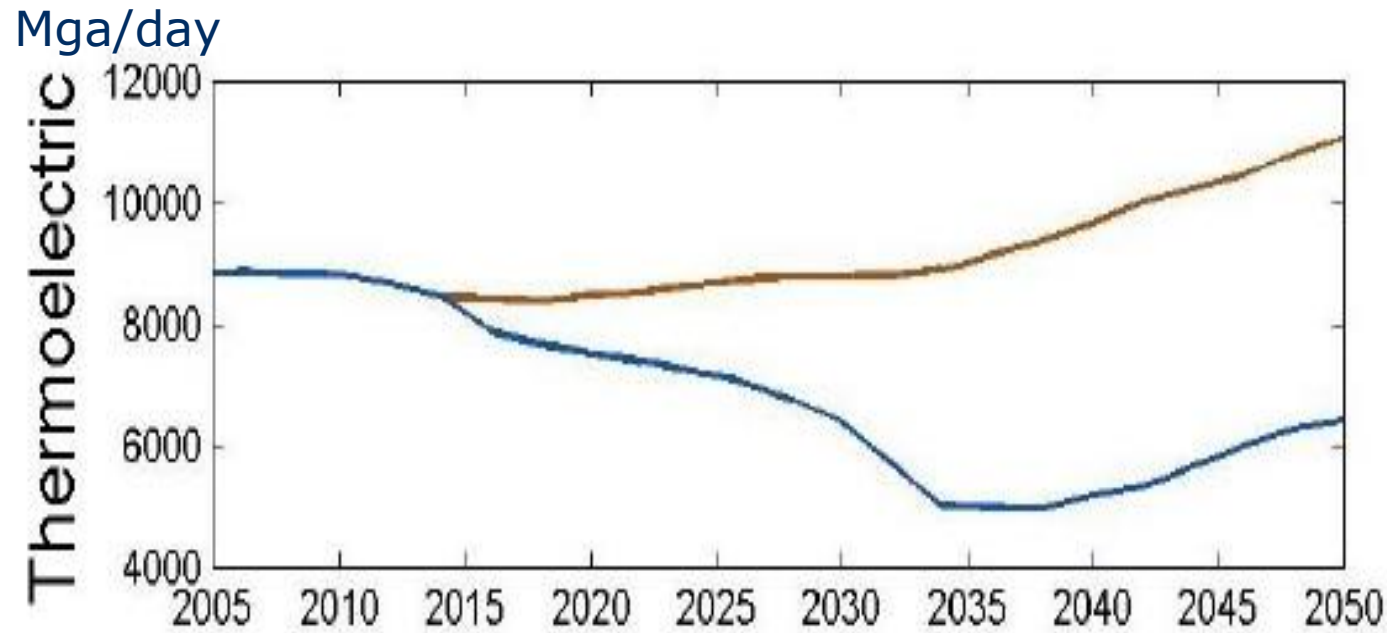
IGSM-WRS-US



Blanc et al., 2013

Evolution of Thermo-electric Water Withdrawals

(Depends on developing Regs. WRT cooling water)



___ Unconstrained Emission

___ 450 Equivalent CO2

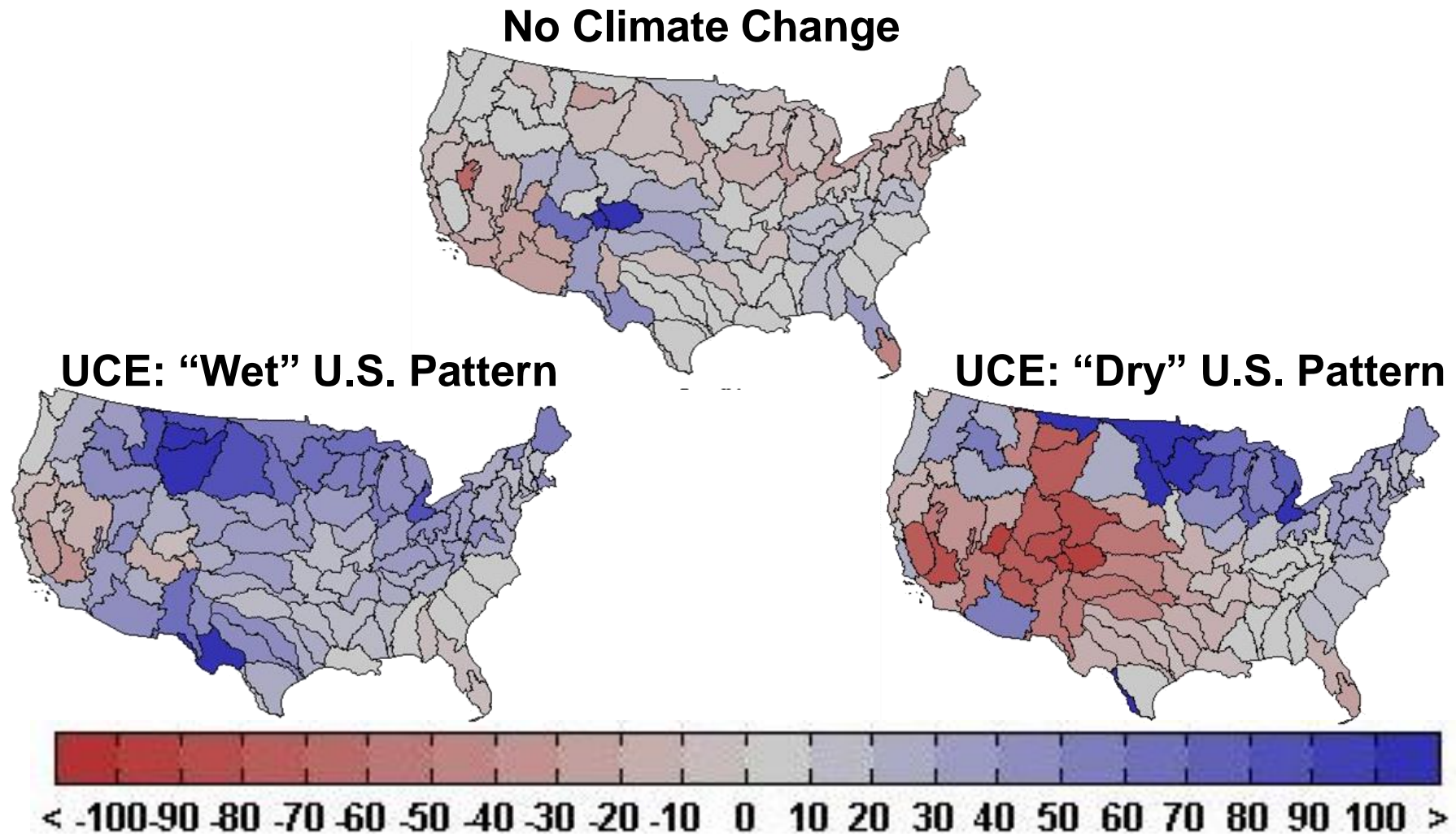
E

WRS

WiCTS



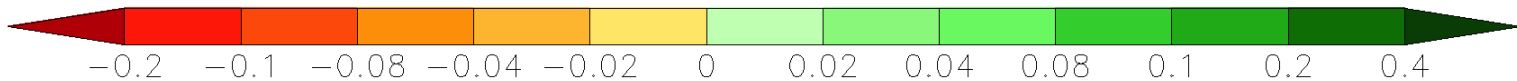
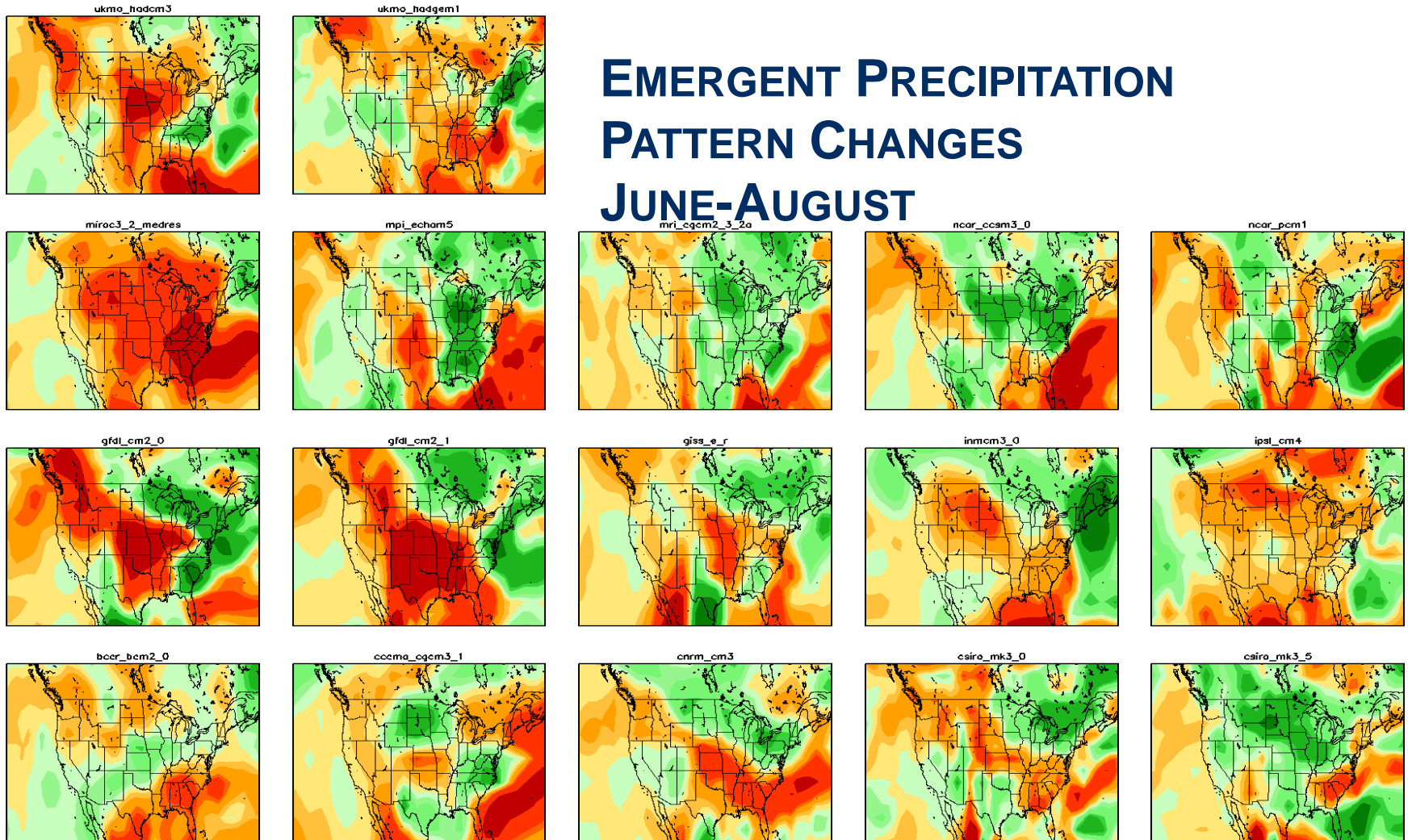
However, water run-off depends strongly on underlying pattern of precipitation and temperature change: E.g. Comparing a relatively “wet” and “dry” pattern



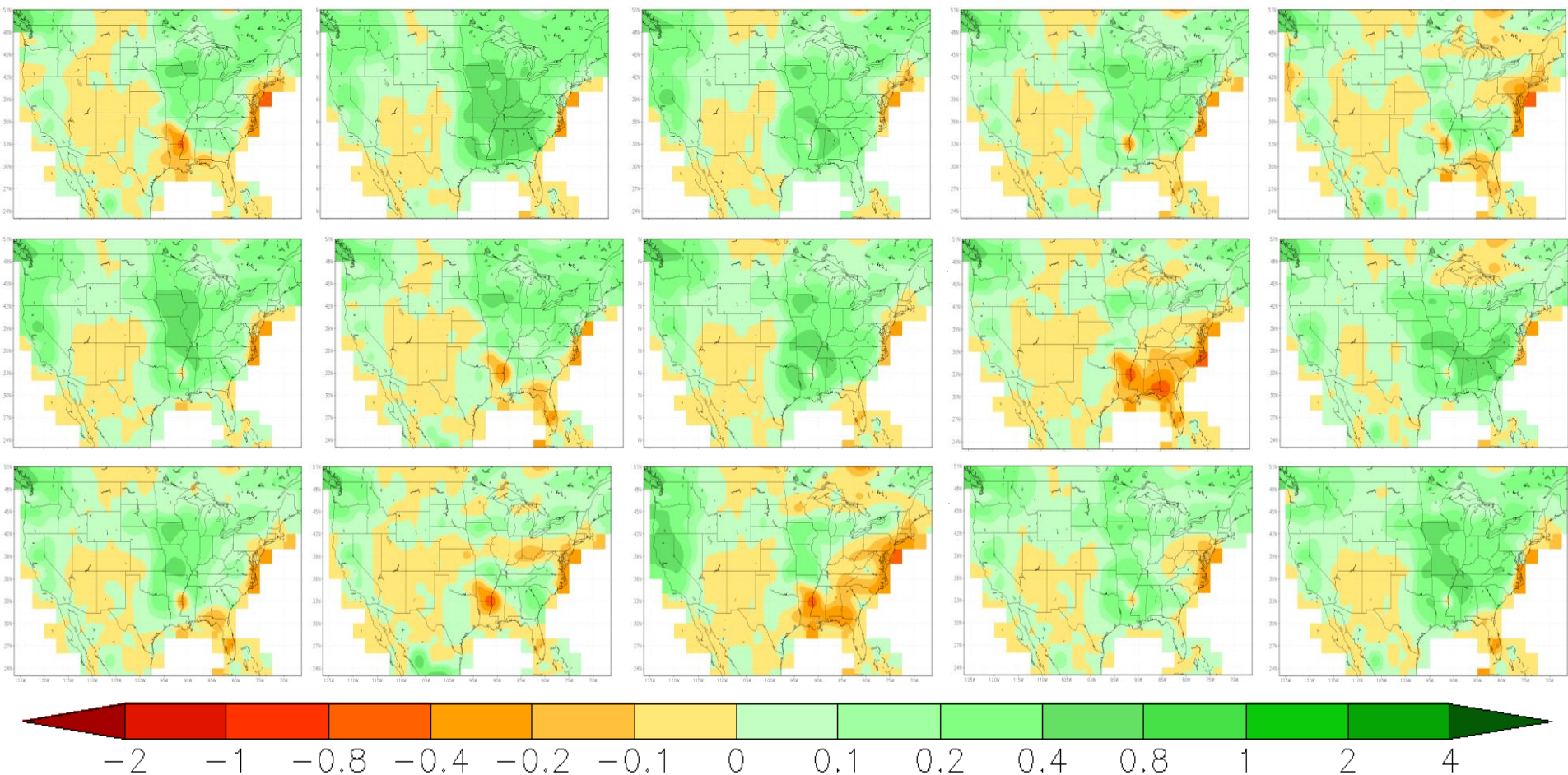
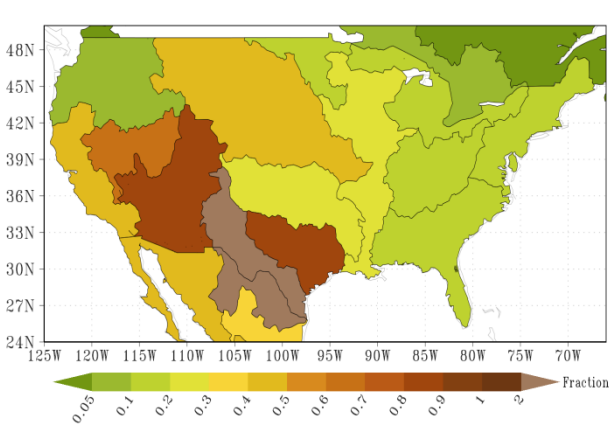
U.S. application: Water Resource System modeling for the U.S., Blanc E., K. Strzepek, C. A. Schlosser, H. Jacoby, A. Gueneau, C. Fant, S. Rausch (2014, *Earth Futures*)

IN FACT A VARIETY OF PRECIPITATION PATTERNS DEPENDING ON UNDERLYING GCM

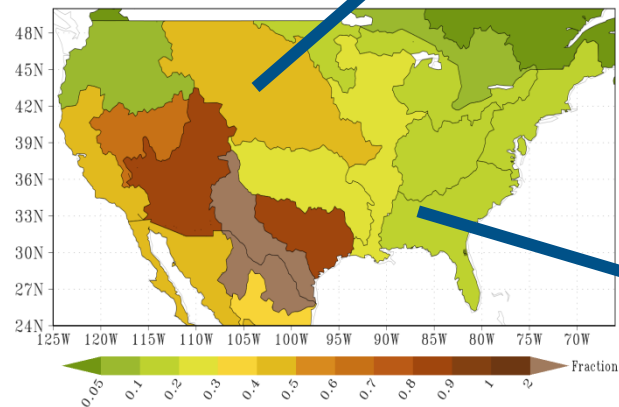
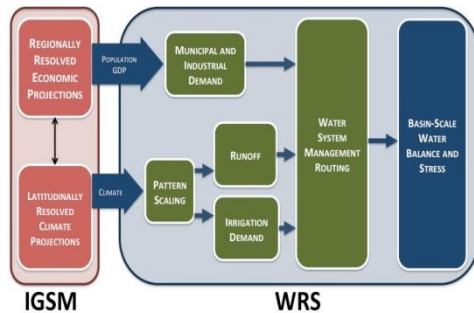
EMERGENT PRECIPITATION PATTERN CHANGES JUNE-AUGUST



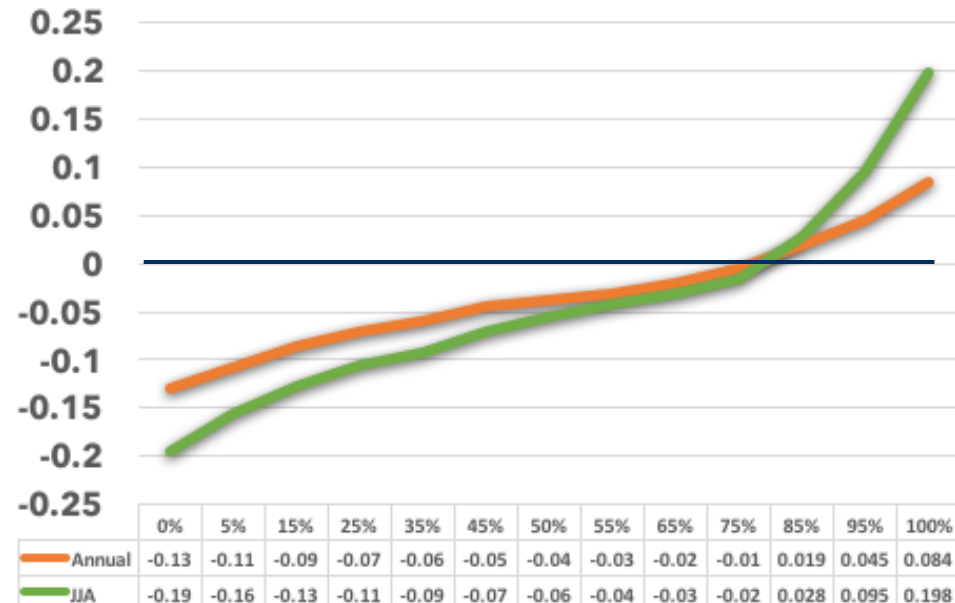
With a Range of Annual Runoff Changes (mm/day) Pattern-Mean Forced Response (2040s-2010s)



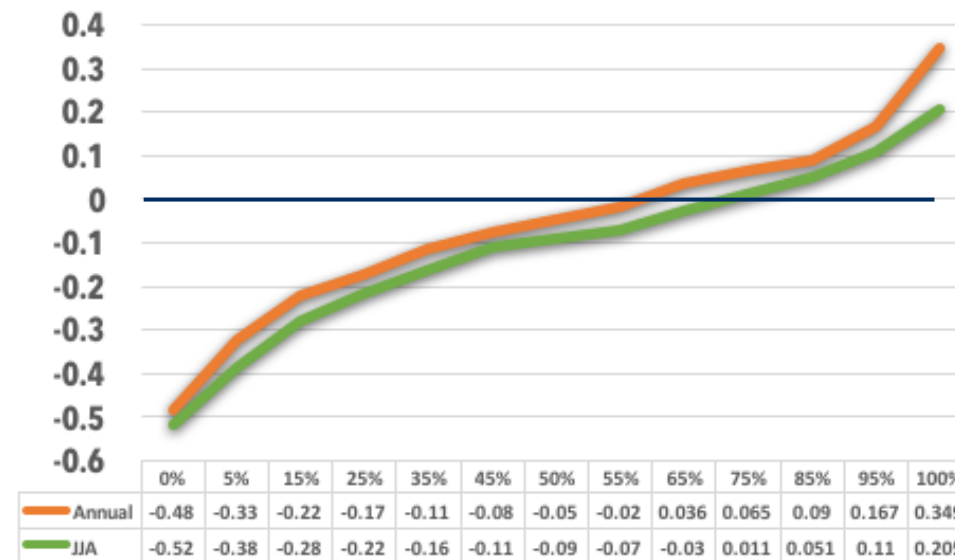
Seasonality matters—JJA vs Annual: Formulate as CDF



Upper Missouri: Distributional Runoff Change 2040s-2010s



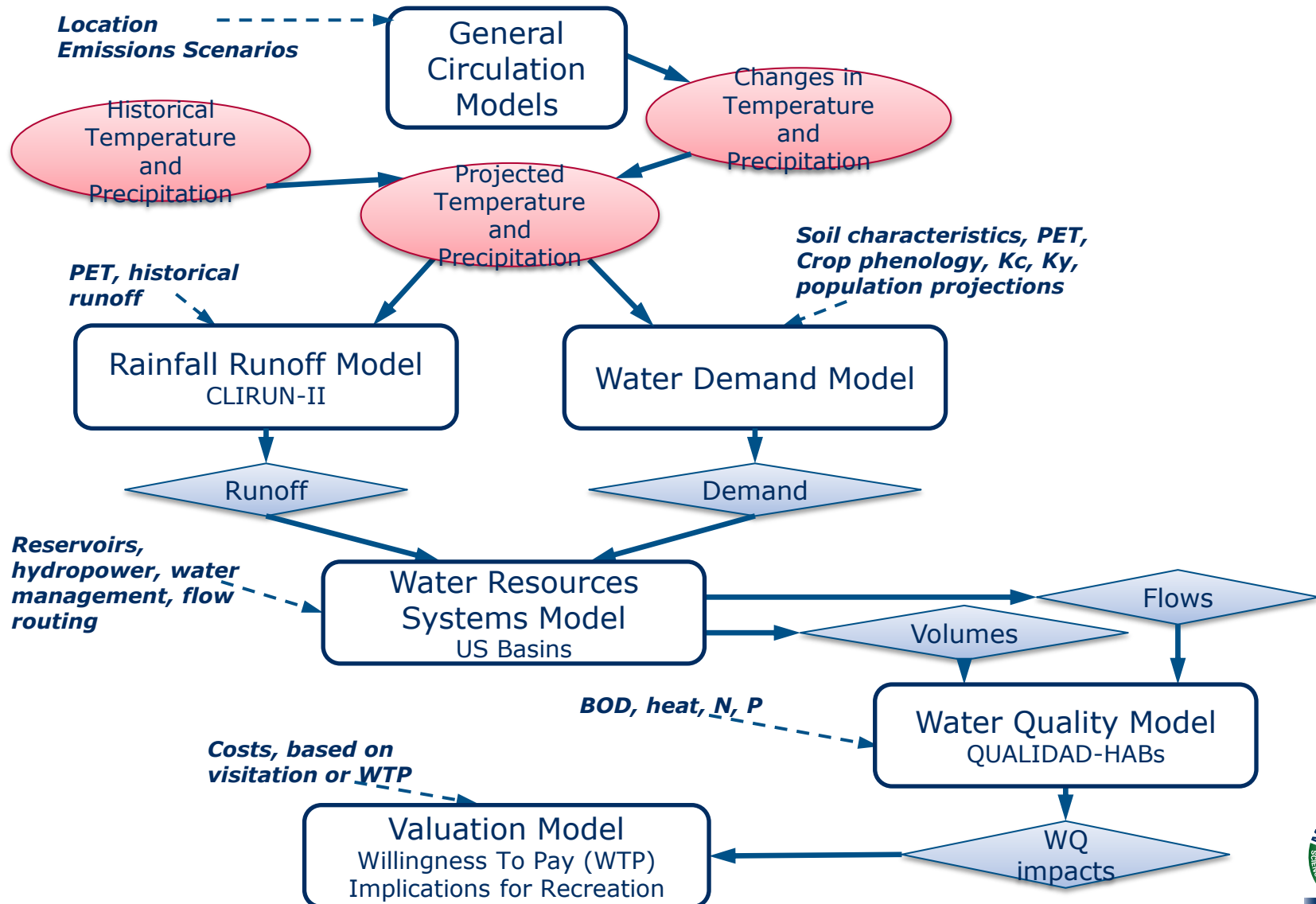
Southeast: Distributional Runoff Change 2040s-2010s



Extend WRS to consider water quality

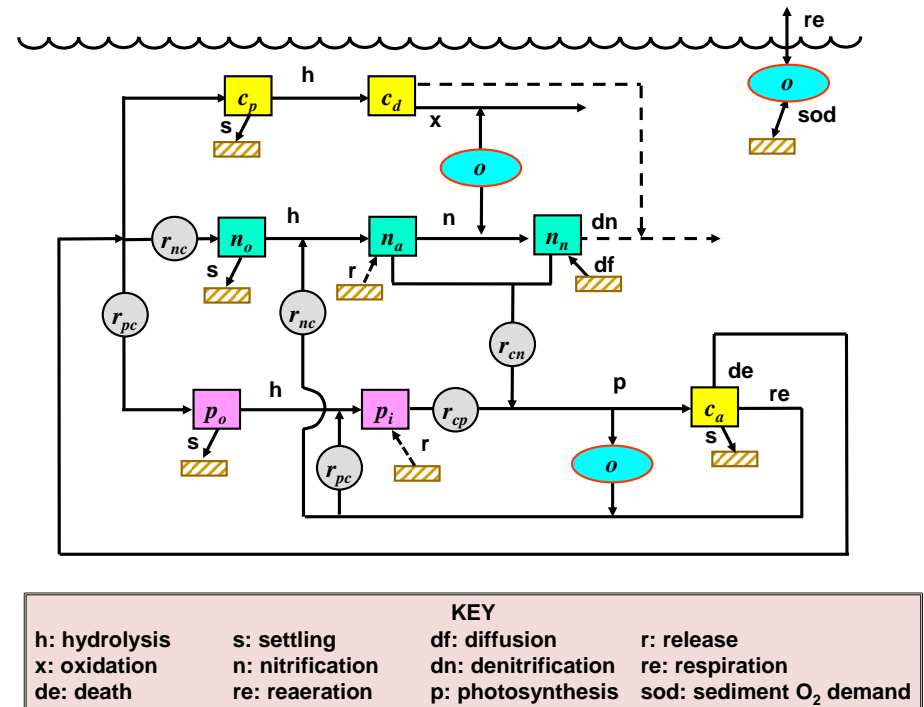
(Collaboration with Industrial Economics and Tufts)

Boehlert et al. 2015; JAMES; Fant et al. 2017; Water; Chapra et al. 2017: ES&T



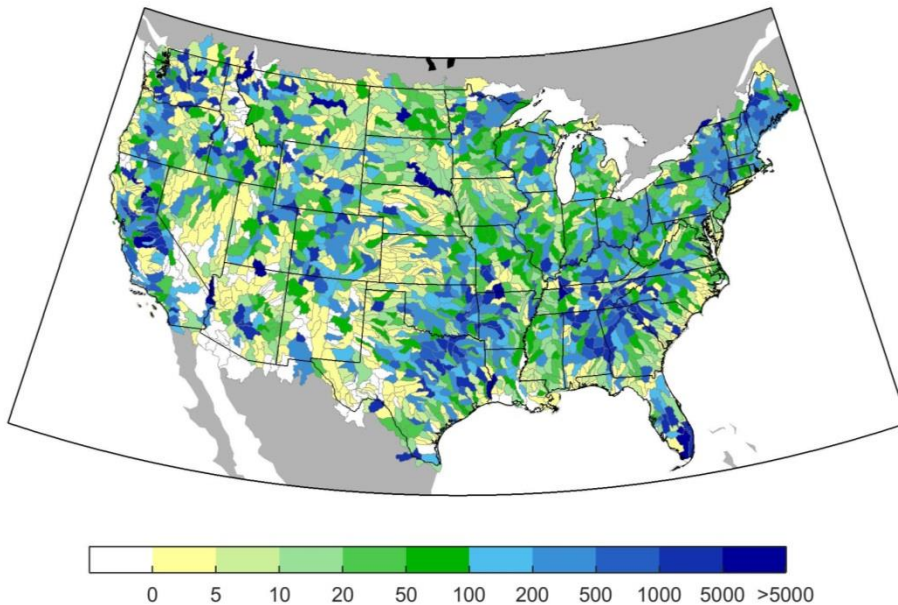
Water quality model (QUALIDAD)

- Same structure over the Contiguous U.S.
- Scenarios and eras (climate & socioeconomic)
 - Business as Usual (Reference)
 - Mitigation Scenarios
- Water Quality Measures
 - Water Temperature
 - Dissolved Oxygen
 - Organic Carbon
 - Nitrates (Ammonia, Nitrogen & Organic)
 - Phosphates (Organic & Inorganic)
 - Phytoplankton (including HABs)



Resolved at 2119 River basins but we often want to report at broader resource regions

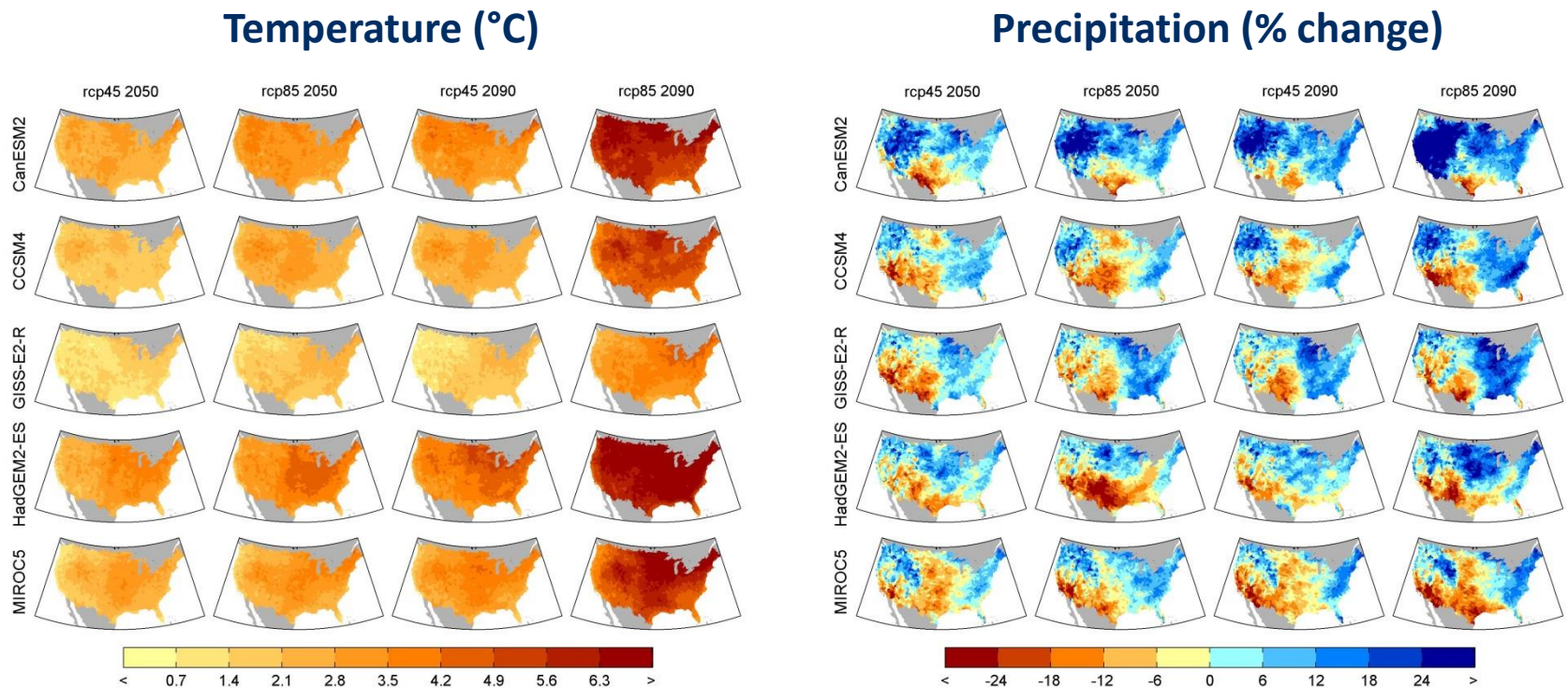
Total reservoir storage (mcm) in each 8-digit HUC



- Basin Boundaries
- Total of 2,119 basins (rivers)
 - based on 8-digit HUCs; developed by USGS

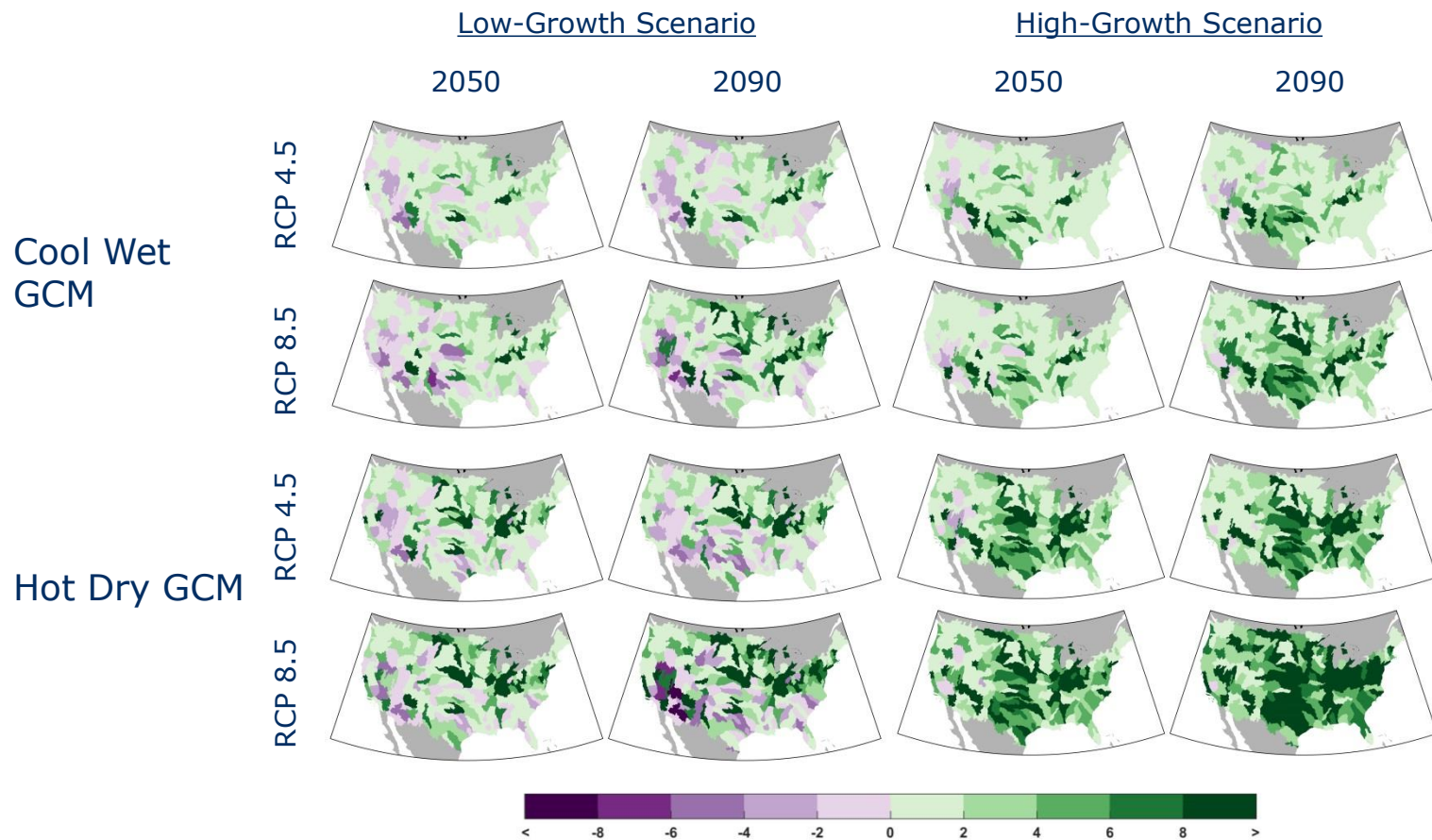
Driven by an Ensemble of Climate change scenarios

- Five GCMs, Two RCPs
- Four “eras” (2030, 2050, 2070, 2090)
- Temperatures rise, precipitation varies spatially
- Large differences between GCMs

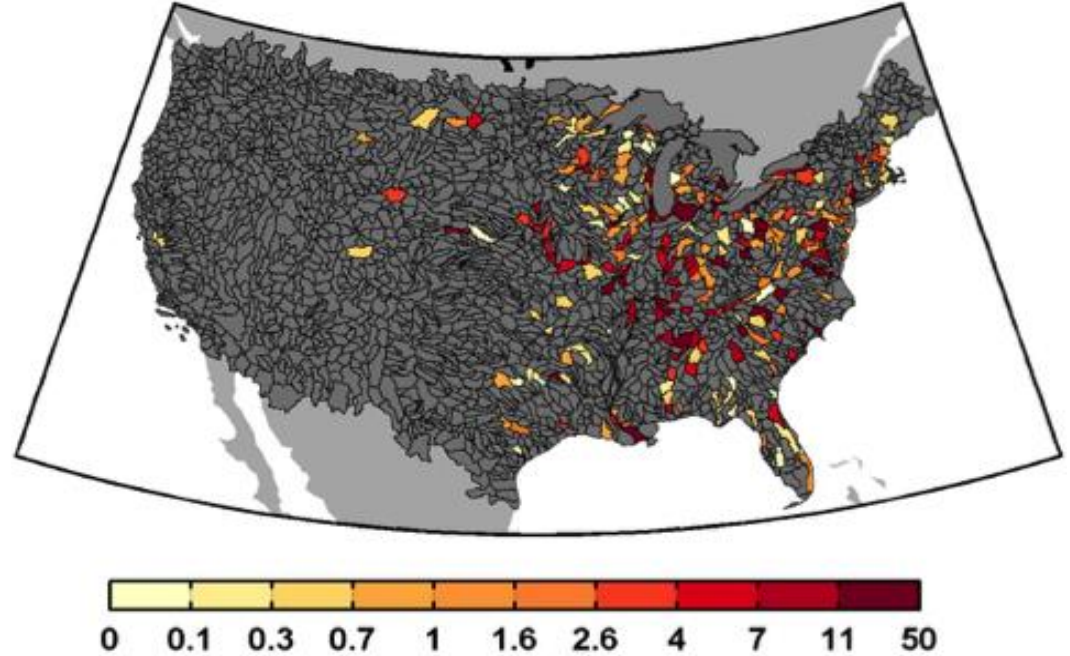
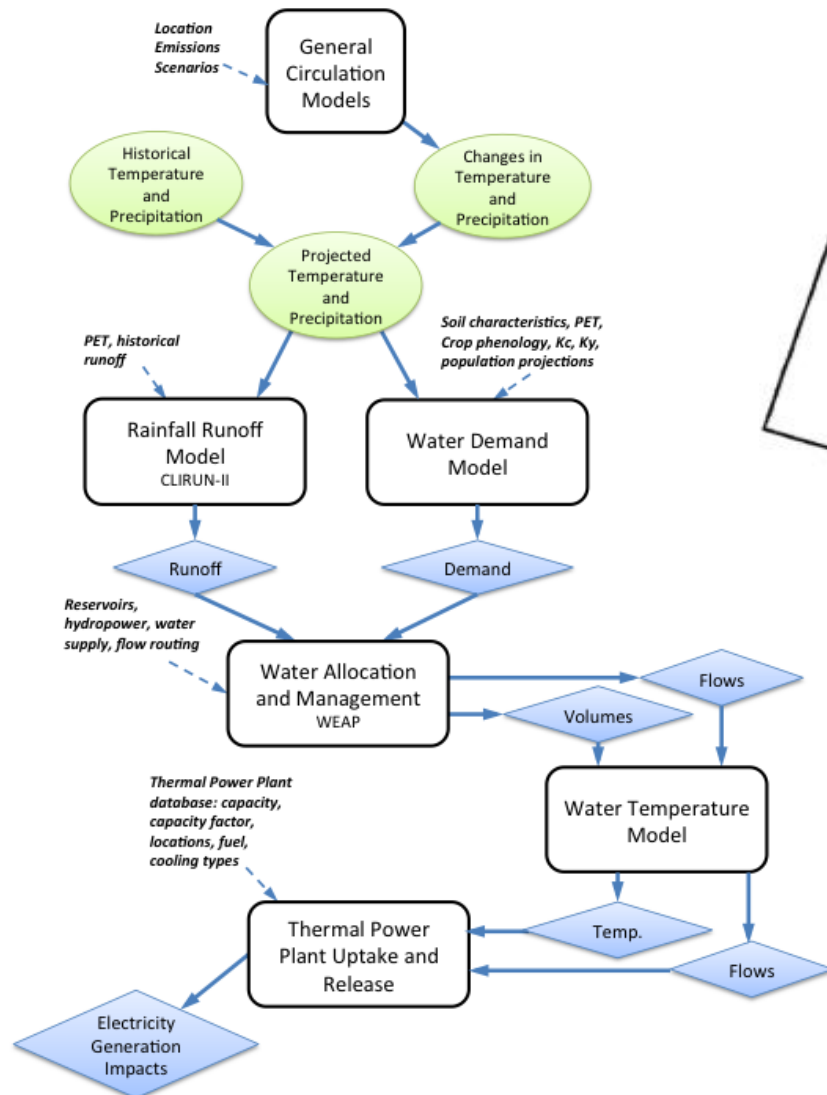


One Strong Result: Major increases in cyanobacteria concentration in lakes and reservoirs, amplified with dryer and hotter conditions (thousands of cells / ml)

- Large differences between climate scenarios and growth scenarios
- Regardless, HAB occurrence increases, particularly in the northeast and midwest



WATER QUALITY—TEMPERATURE MODELING For THERMAL COOLING



Once-through cooling
Total annual generation (in TWh)

Impacts on Annual Generation in US (lower 48) in 2050

Control Gen.	Region	CAM			MIROC		
		'CS3REF	'POL4.5'	'POL3.7'	'CS3REF	'POL4.5'	'POL3.7'
9%	'NE'	3%	-2%	-2%	0%	-4%	-5%
34%	'SE'	-8%	-11%	-22%	-10%	-11%	-24%
23%	'MW'	5%	-2%	12%	1%	-4%	9%
6%	'NP'	-13%	16%	19%	-17%	12%	11%
16%	'SP'	4%	-1%	-9%	1%	-3%	-10%
10%	'NW'	2%	1%	-31%	0%	0%	-30%
2%	'SW'	2%	-12%	101%	1%	-12%	101%
	Total	-1%	-4%	-6%	-4%	-5%	-9%



And Extension to Hydropower

B. Boehlert et al. / Applied

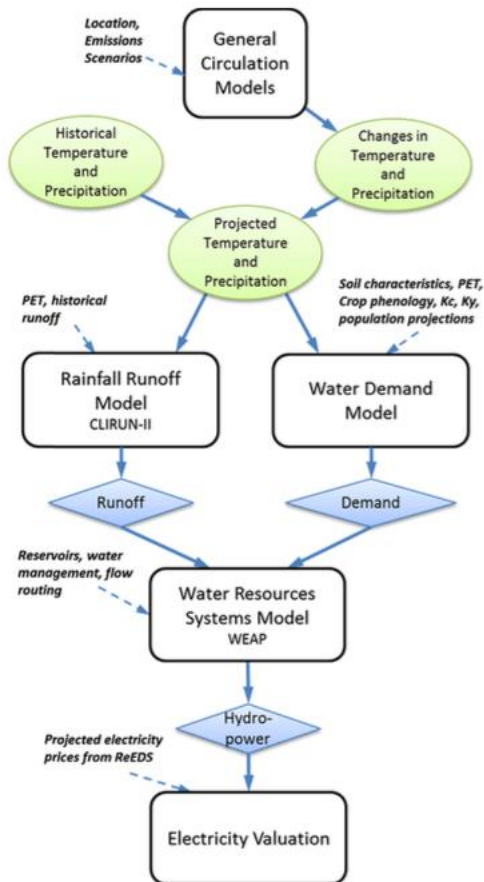
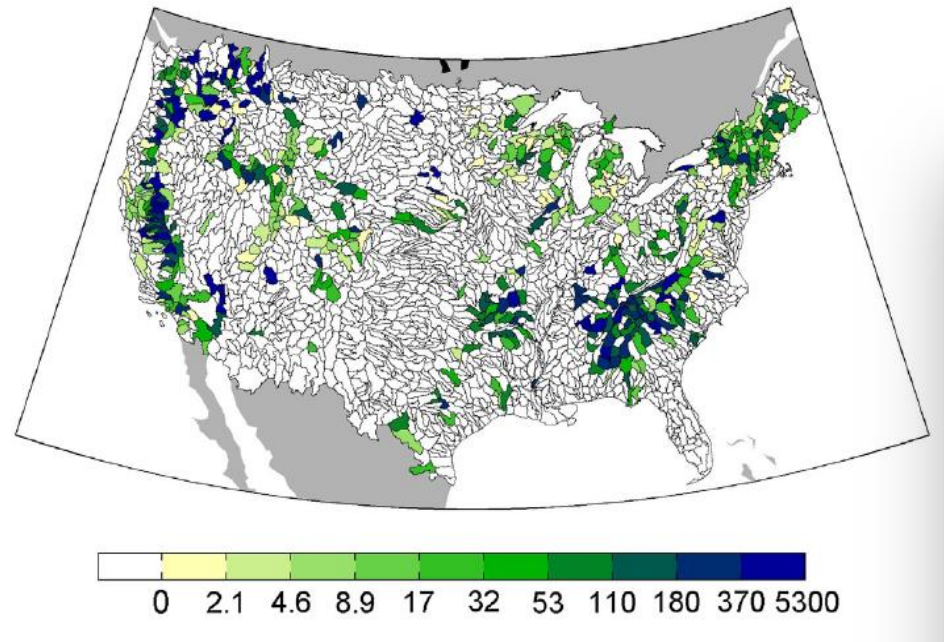


Fig. 1. Analytical framework.



Current capacity: Megawatts

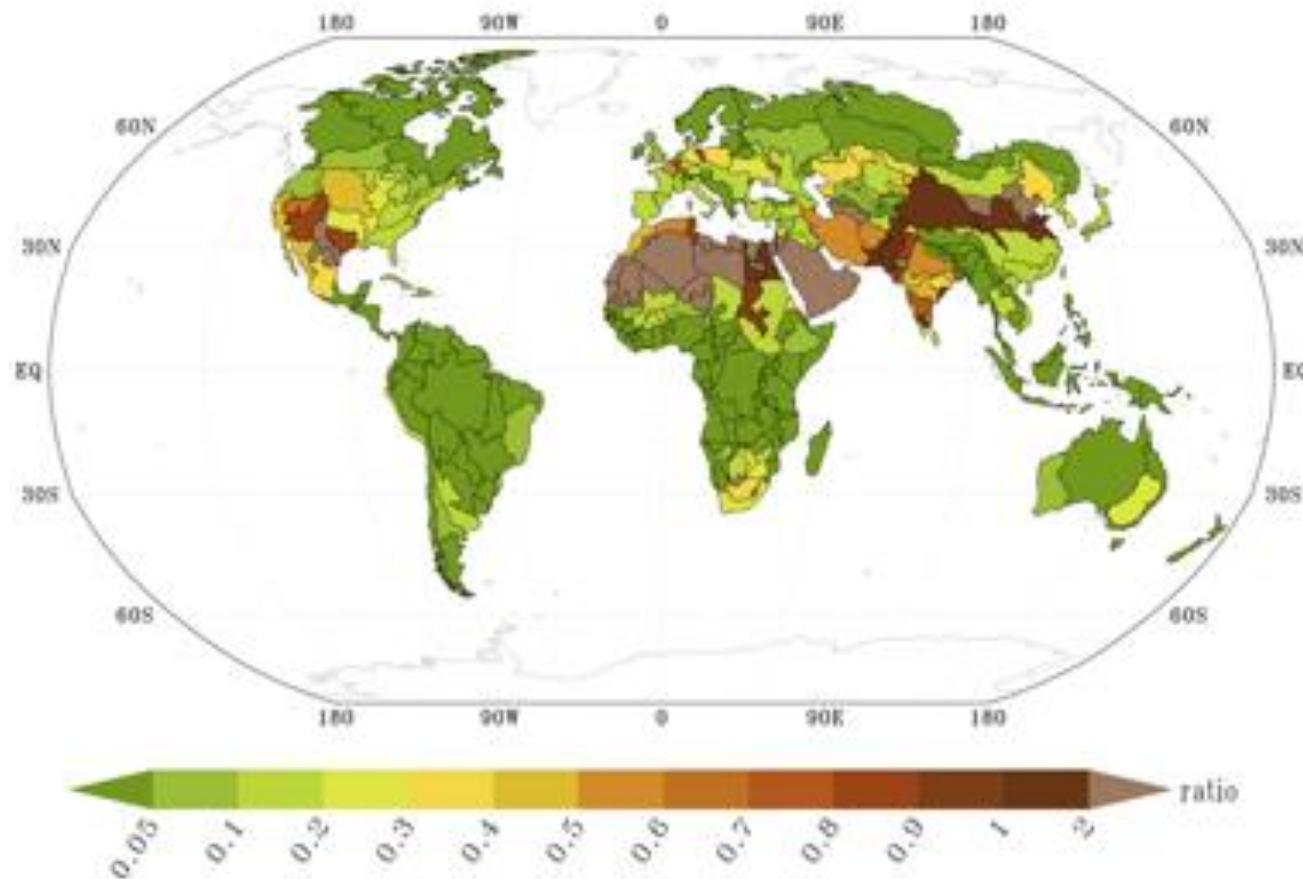
Seasonality perhaps critical: greatest reductions during peak summer demand

Table 2
Average seasonal change in 2050 hydropower generation from the control for each emissions scenario, at the 2-digit HUC level, under the average across pattern scaled GCM projections. Note: Excludes the Great Lakes 2-Digit HUC.

2-Digit HUC	DEC-JAN-FEB			MAR-APR-MAY			JUN-JUL-AUG			SEP-OCT-NOV		
	REF	POL4.5	POL3.7	REF	POL4.5	POL3.7	REF	POL4.5	POL3.7	REF	POL4.5	POL3.7
New England	18%	11%	10%	2%	1%	1%	-3%	-5%	-4%	0%	-1%	0%
Mid Atlantic	7%	5%	5%	-3%	-2%	-2%	-2%	-3%	-8%	-2%	-2%	-3%
South Atlantic Gulf	0%	0%	0%	-5%	-4%	-4%	-2%	-1%	0%	-2%	-1%	-1%
Ohio	1%	1%	1%	-2%	-1%	-1%	0%	-1%	-1%	-2%	-1%	-1%
Tennessee	-1%	0%	0%	-2%	-2%	-2%	-1%	-1%	0%	-2%	-1%	-1%
Upper Mississippi	1%	0%	0%	1%	0%	0%	0%	-1%	0%	0%	0%	0%
Lower Mississippi	3%	2%	2%	-18%	-14%	-13%	-18%	-14%	-13%	-6%	-4%	-4%
Souris-Red-Rainy	0%	-4%	-3%	7%	1%	0%	-4%	-5%	-1%	-3%	-4%	-2%
Missouri	-12%	-12%	-10%	14%	6%	5%	-12%	-13%	-10%	-16%	-15%	-14%
Arkansas-White-Red	1%	1%	1%	-8%	-6%	-5%	-6%	-5%	-4%	-5%	-4%	-3%
Texas Gulf	-4%	-1%	-1%	-14%	-10%	-9%	-16%	-9%	-8%	-13%	-9%	-8%
Rio Grande	-8%	-6%	-6%	-8%	-7%	-7%	-16%	-12%	-11%	-7%	-6%	-6%
Upper Colorado	-8%	-9%	-9%	7%	3%	2%	-15%	-12%	-12%	-10%	-10%	-10%
Lower Colorado	32%	14%	9%	33%	10%	7%	42%	26%	21%	3%	1%	-1%
Great Basin	14%	4%	3%	28%	16%	12%	-14%	-11%	-11%	-14%	-15%	-18%
Pacific Northwest	23%	13%	12%	14%	9%	8%	-14%	-12%	-9%	-5%	-5%	-5%
California	10%	6%	5%	7%	4%	3%	-6%	-4%	-4%	-11%	-8%	-8%
TOTAL	13%	7%	6%	9%	5%	4%	-9%	-8%	-7%	-5%	-5%	-4%



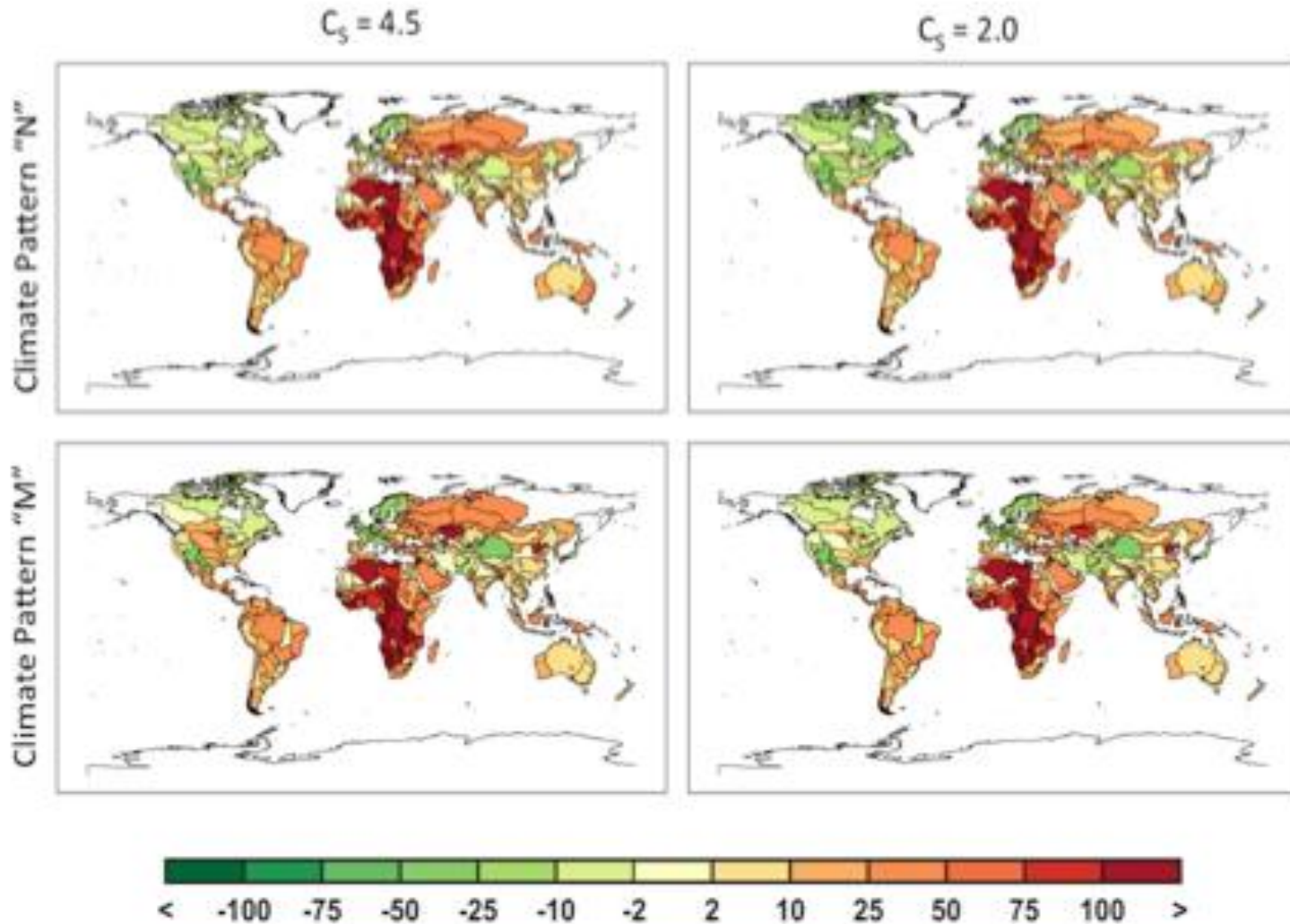
Global Application: Current (2001-2020) Water Stress



Current water Stress (unit-less ratio of use to annual availability) simulated average 2001-2020

Implications: For 2050 (2041-2060)

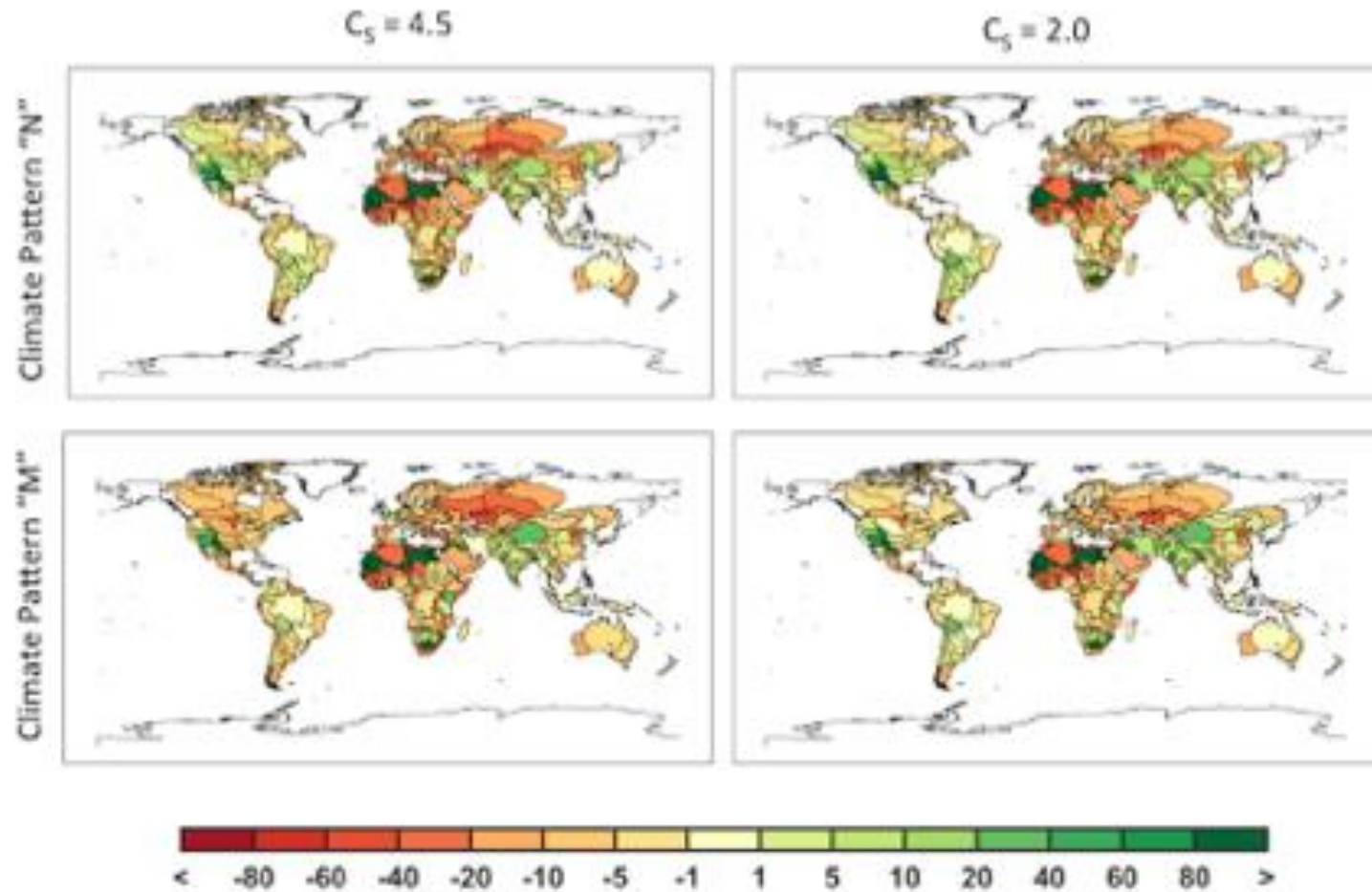
(% change in WSI index from present (2001-2020))



Simulated for two climate patterns (M and N) and two levels of climate sensitivity. Much of stress increase is due to increased demand from growth, but climate often an aggravating factor.

Climate Impact: Run-off changes for 2050 (2041-2060)

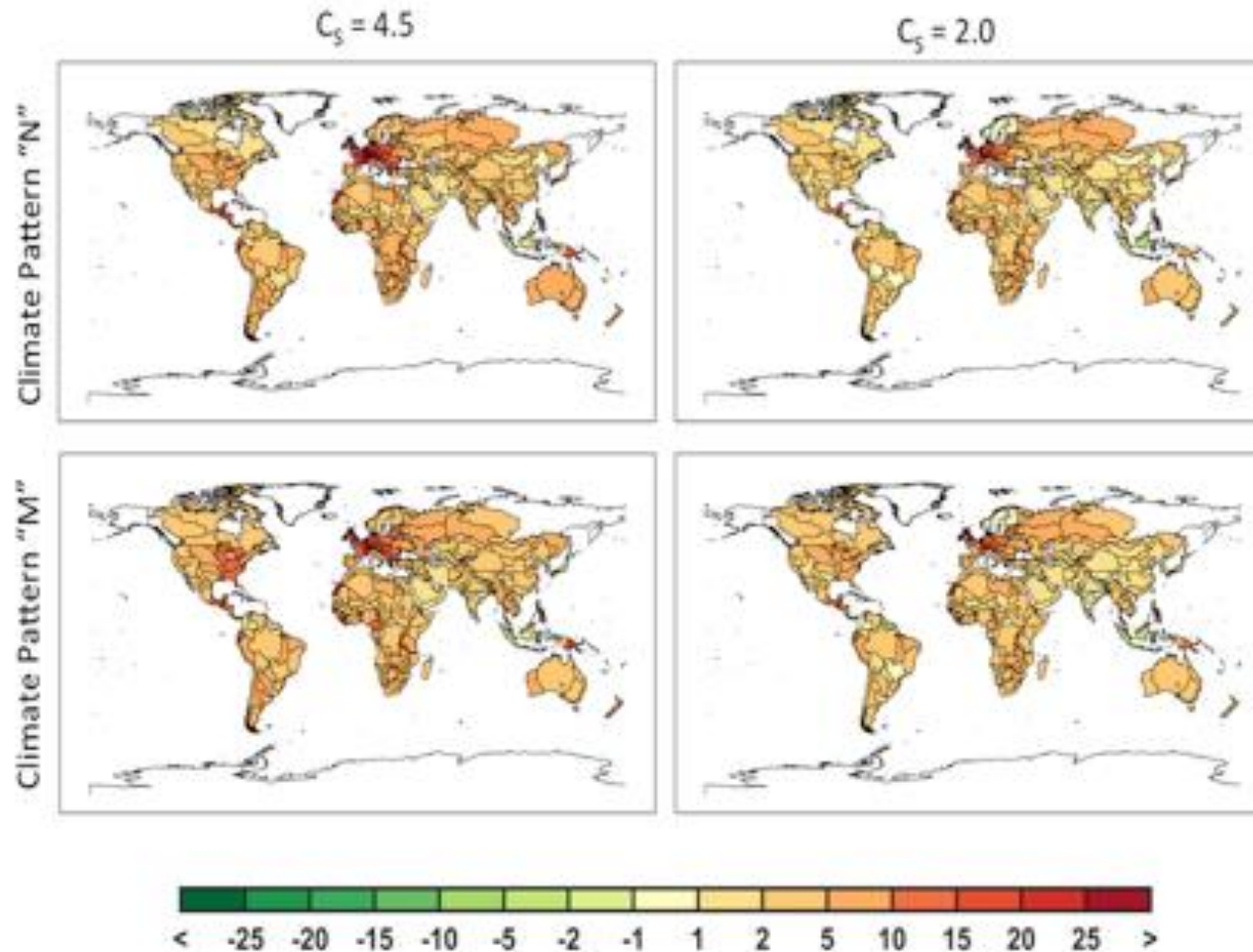
(% change in runoff from present (2001-2020))



Simulated for two climate patterns (M and N) and two levels of climate sensitivity. Run-off changes isolate one the climate effect on water supply.

Climate Impact: Irrigation demand changes for 2050 (2041-2060)

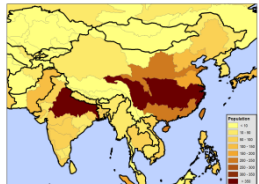
(% change from present (2001-2020))



Simulated for two climate patterns (M and N) and two levels of climate sensitivity. Run-off changes isolate one the climate effect on water supply.

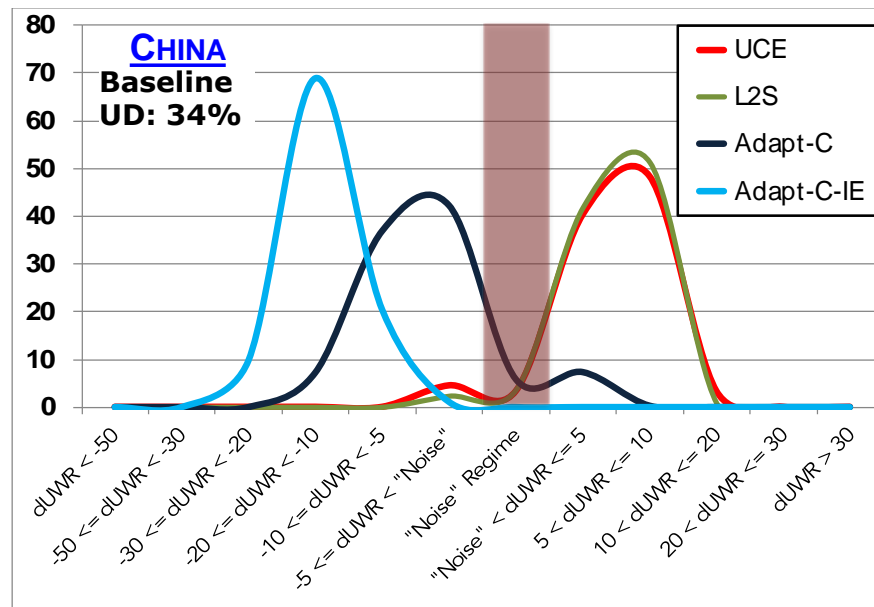
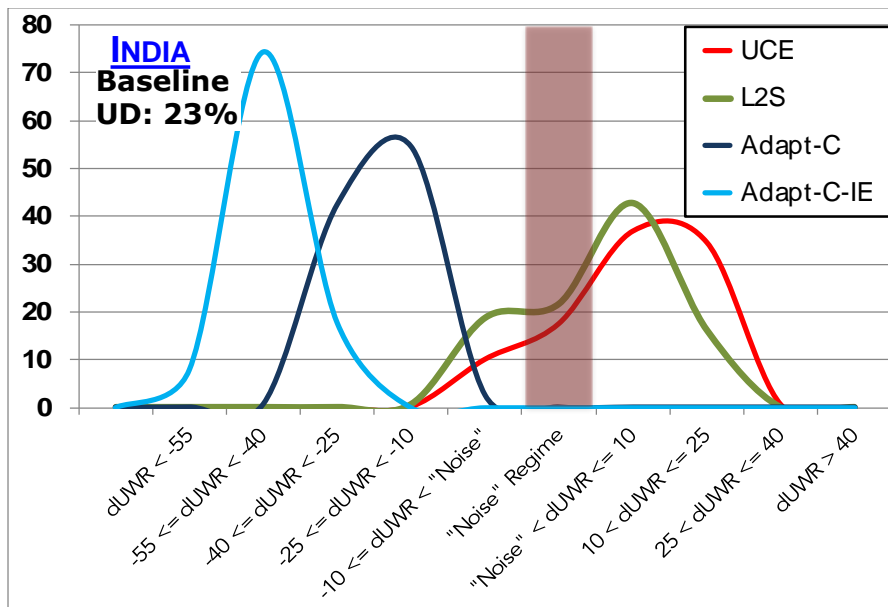
Global modeling—some Caveats

- A small sample of possible climate (and growth) scenarios so caution in specific regional results.
- As many have found, climate not necessarily the biggest concern but often one that aggravates other stresses.
- No adaptation measures were considered...projection suggest a call to focus on adaptation.
- Climate effects on both run-off (water supply) and irrigation requirements (water demand) both mostly appear to aggravate potential water stress.
- Greater resolution needed to assess specific adaptation needs along with need to consider predictability of climate and for highly resolved geography.



COMBINING MITIGATION AND ADAPTATION: RISK REDUCTION SEEN IN UNMET WATER DEMANDS.

CHANGE (%) IN UNMET DEMAND BY 2050



Schlosser et al. (2017, forthcoming)

Adaptation Scenarios

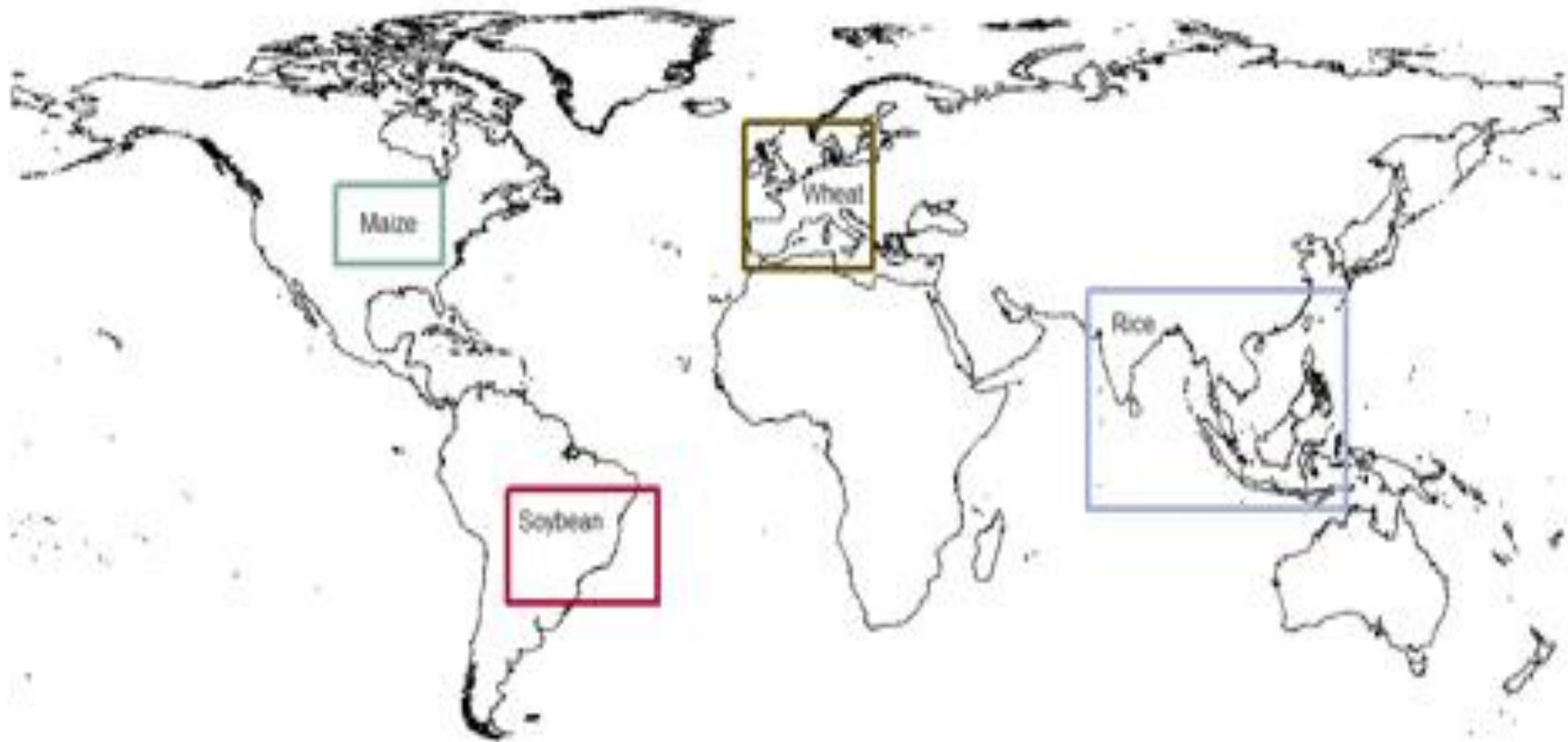
Adapt-C: UCE with lined canals
Adapt-C-IE: Adapt-C with high efficiency sprinklers

Total Cost (Billions 2000 US\$)

	China	India
Adapt-C	35	23
Adapt-C-IE	142	114



Future Yields of major crops—ultimately implications for land requirements in 4 “bread basket” regions

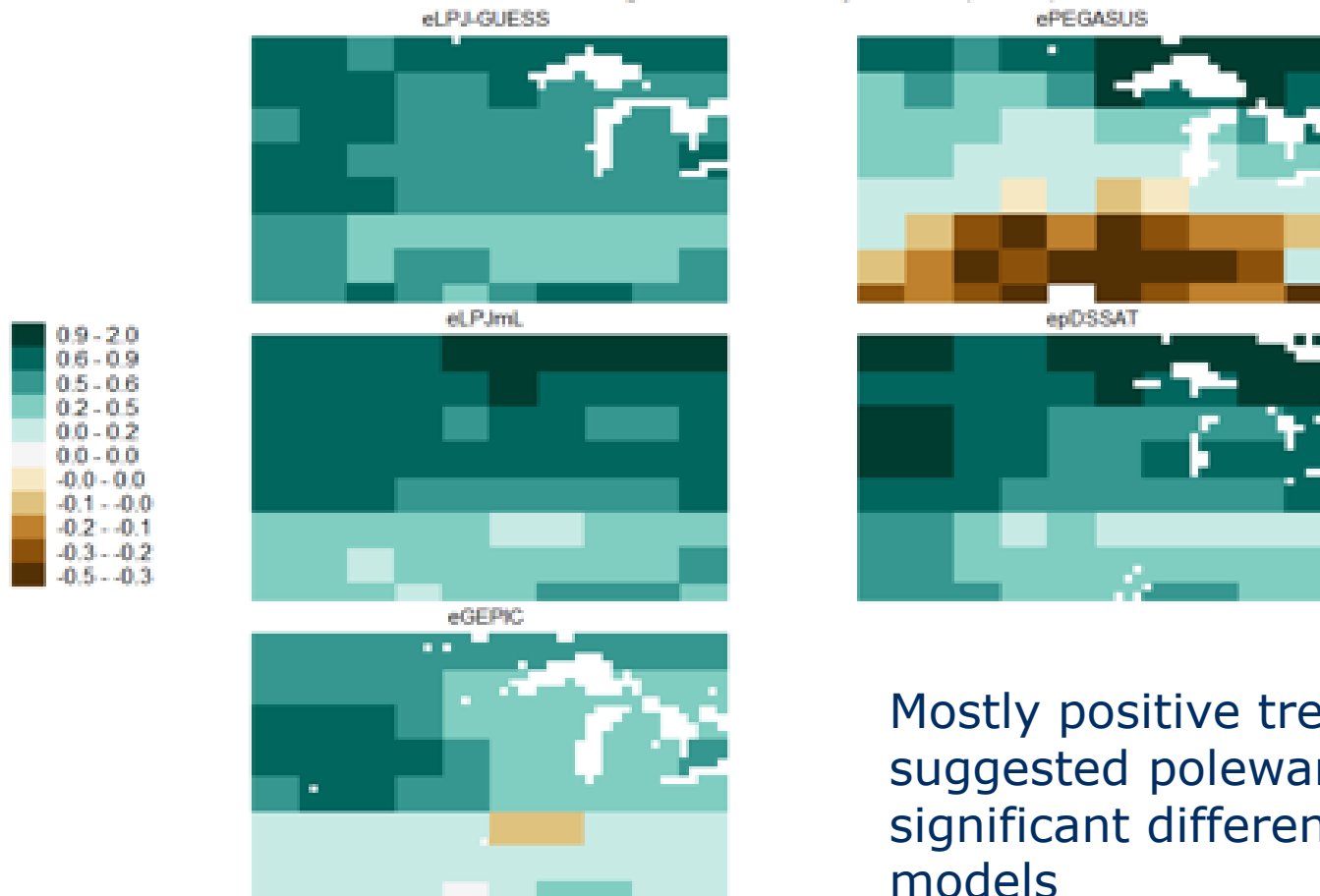


We have used a technique to “train,” statistically a simple model to replicate results of major Globally Gridded Crop Model (GGCM) results archived as part of the AGMIP (LPJ-GUESS, LPJmL, PEGASUS, DSSAT, GEPIC)



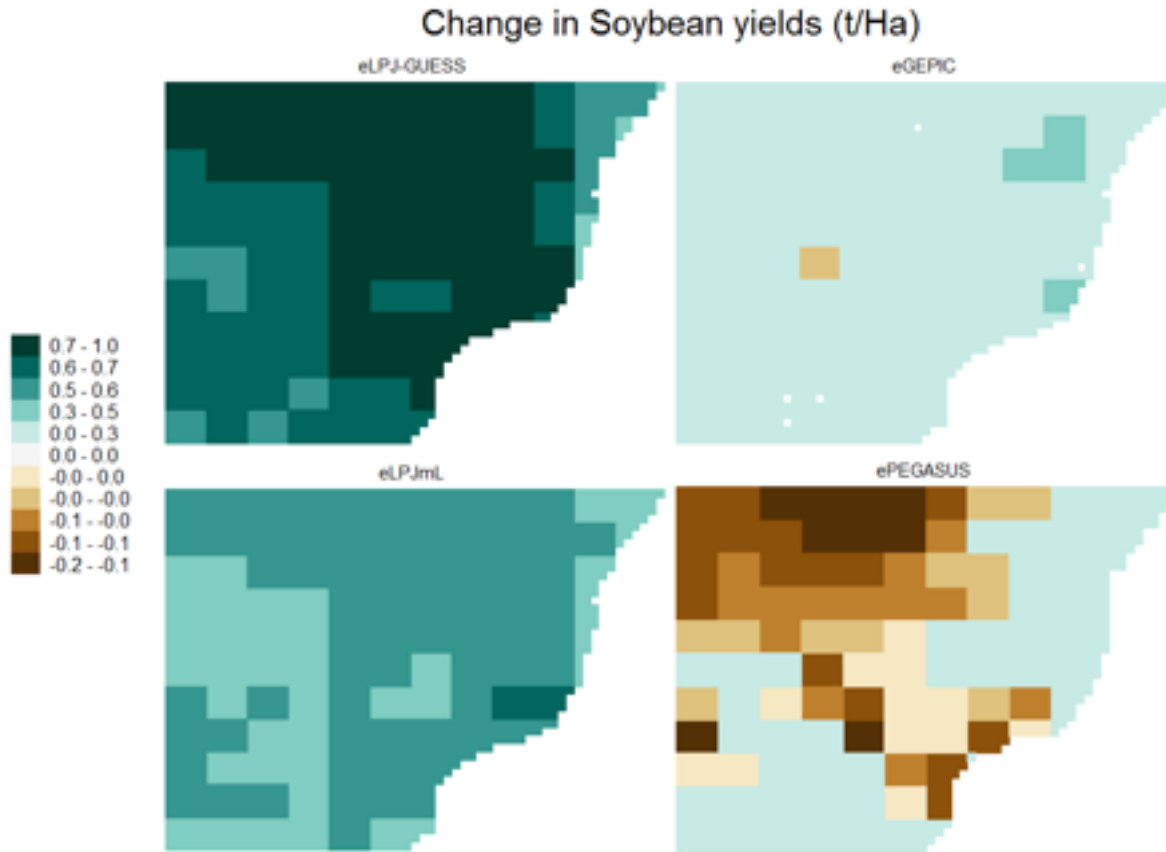
Maize in North America (averaged over climate scenarios) assessed with a yield emulator of major globally gridded crop

Change in Maize yields (t/Ha)



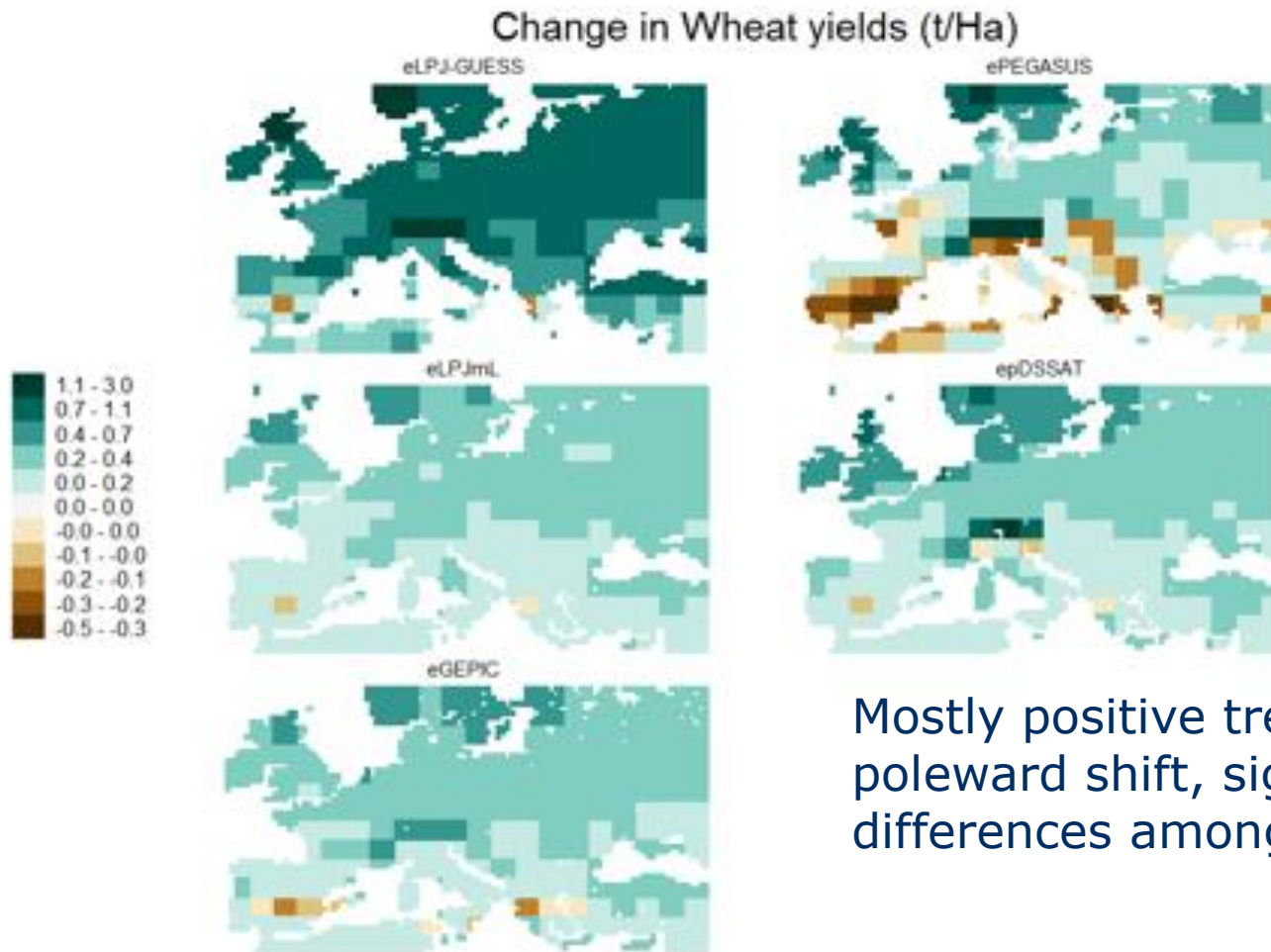
Mostly positive trend, but
suggested poleward shift,
significant differences among the
models

Soybeans in Brazil (averaged over climate scenarios)



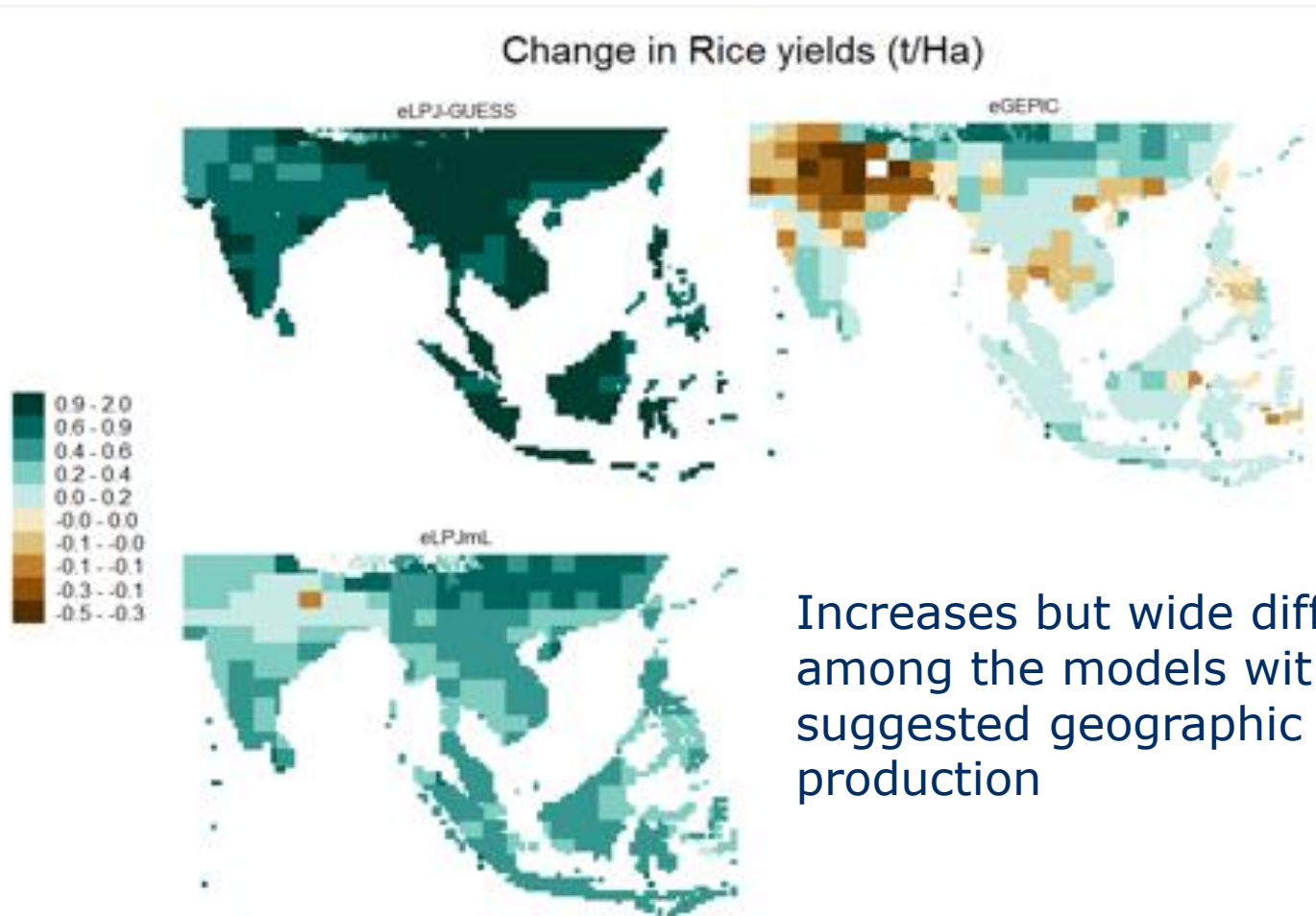
Significant differences among the models both in pattern and overall impact.

Maize in North America



Mostly positive trend, suggested poleward shift, significant differences among the models

Upland rice in South and Southeast Asia (averaged over climate scenarios)



Increases but wide differences among the models with suggested geographic shifts in production

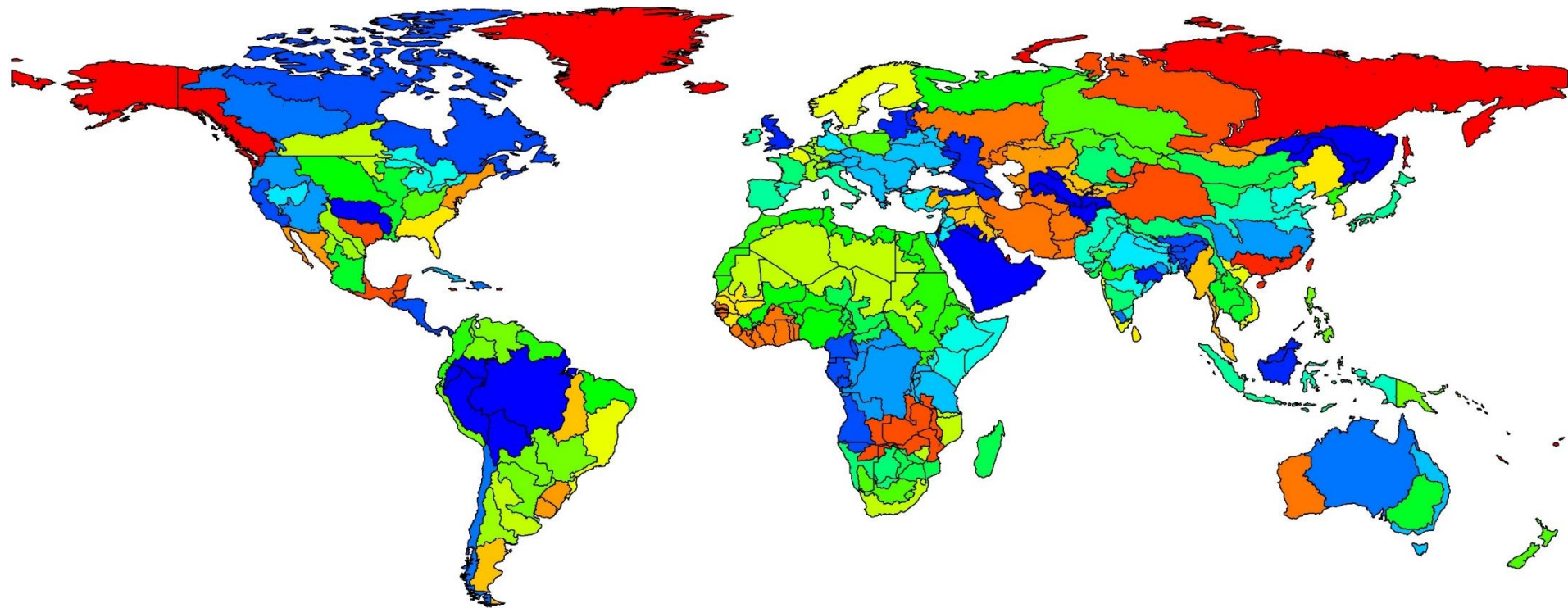
Linking water to irrigation and land use: methodology

Methods to explicitly represent irrigated agriculture in the MIT Integrated Global System Model (IGSM)

- Develop supply functions for additional irrigable land for 126 water regions using WRS
- Irrigable land supply curves are built on water region-level estimates of water availability, and the costs of (1) improving irrigation efficiency and (2) increasing water storage
- Irrigable land supply curves are included in the MIT Economic Projection and Policy Analysis (EPPA) model
- Irrigable land supply curves can be adjusted to account for changes in water availability estimated by the IGSM–Water Resource System (IGSM-WRS) model

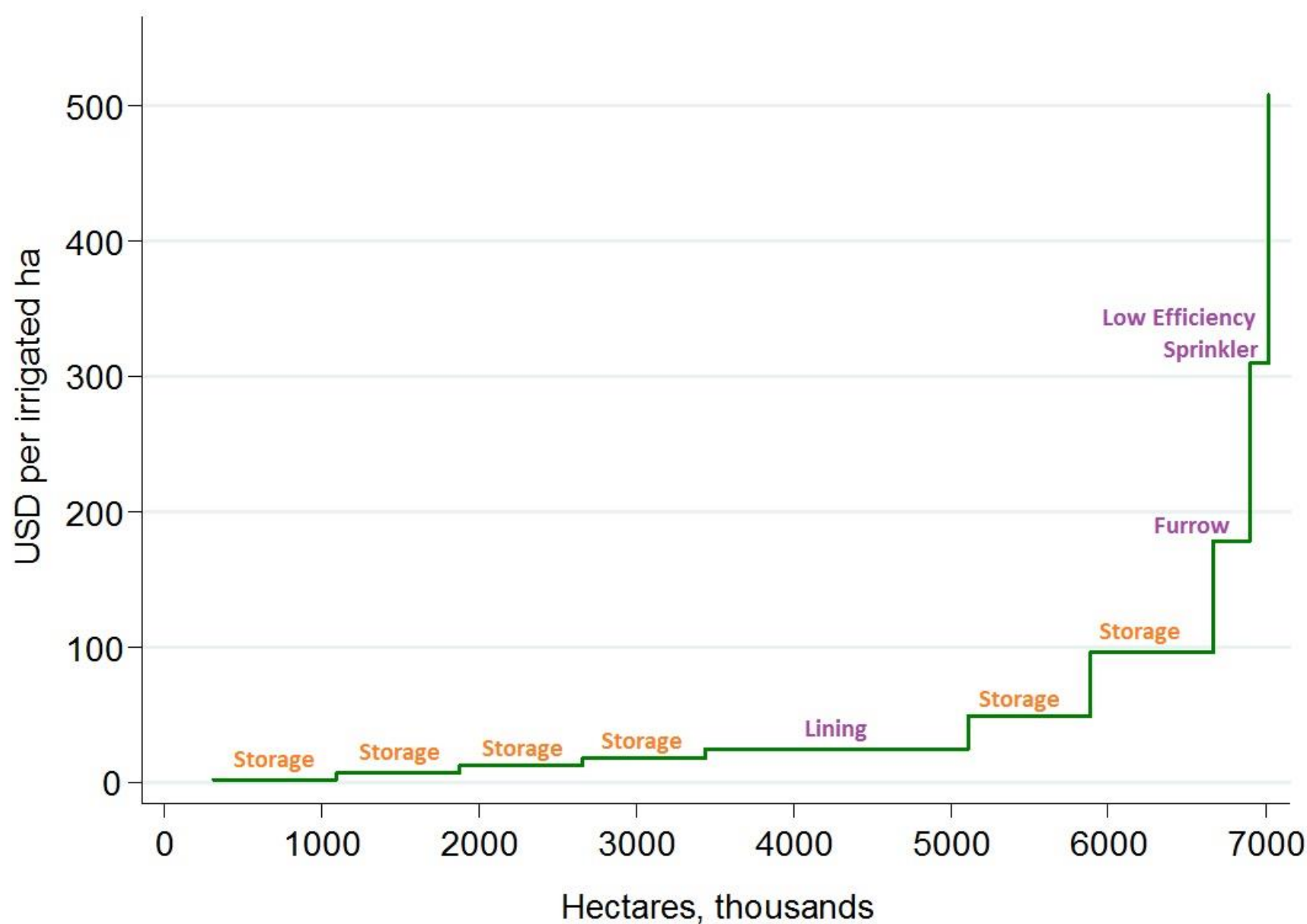
Irrigable land supply curves

- Supply curves for additional irrigable land are estimated for 126 water regions, built on 282 large river basins (Assessment Sub-Regions) identified by the International Food Policy Research Institute (IFPRI)

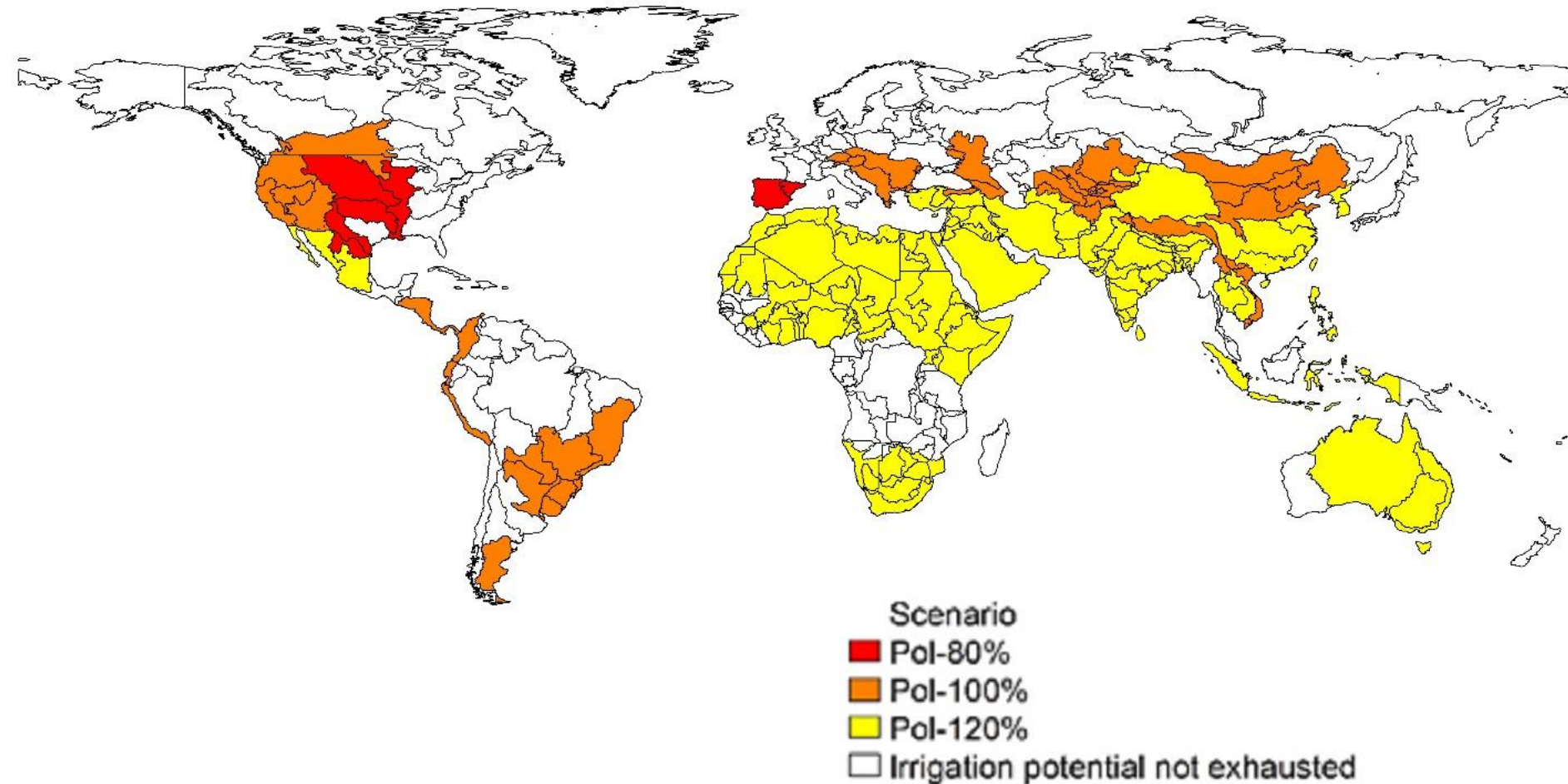


Large river basins (lines) and water regions (colors)

Supply curve for an additional irrigable land built up from estimates of cost to increase storage (up to 10 separate additions) reduce conveyance loss, and improve efficiency of water use



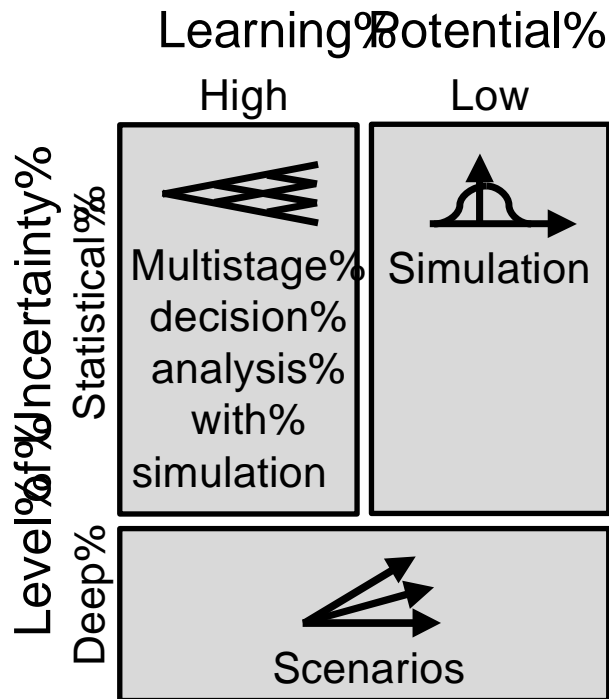
Example: Under growth in food demand demand, population regions coming up against irrigable land supply constraints (no



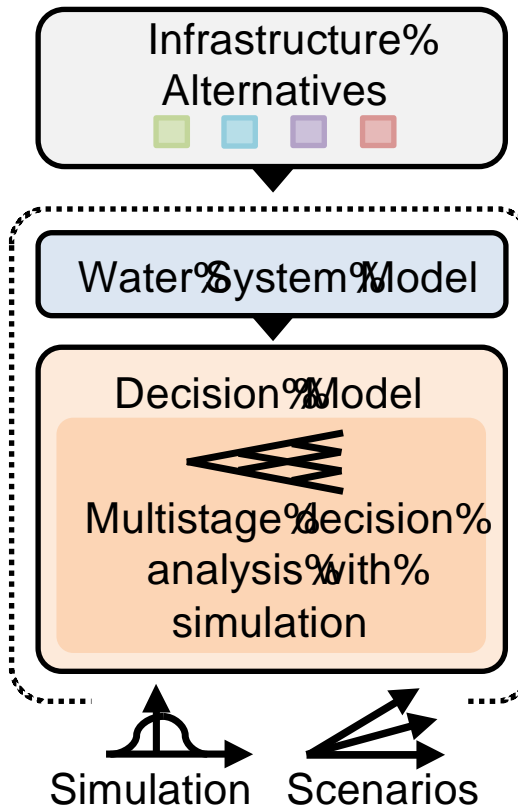
Water regions operating at maximum irrigation potential in 2050

A modeling framework for decision making under uncertainty

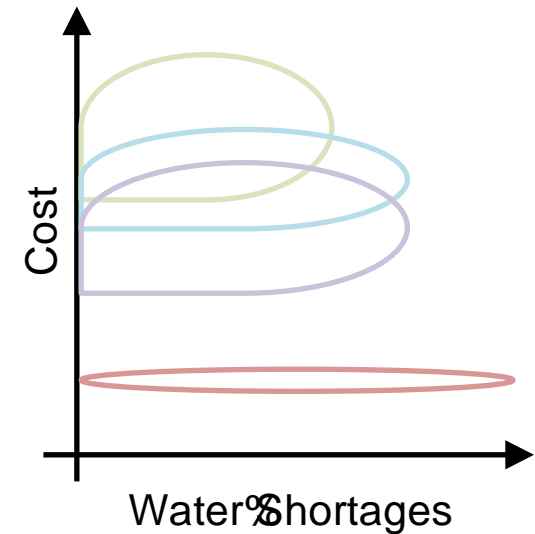
1. Uncertainty Categorization



2. Modeling

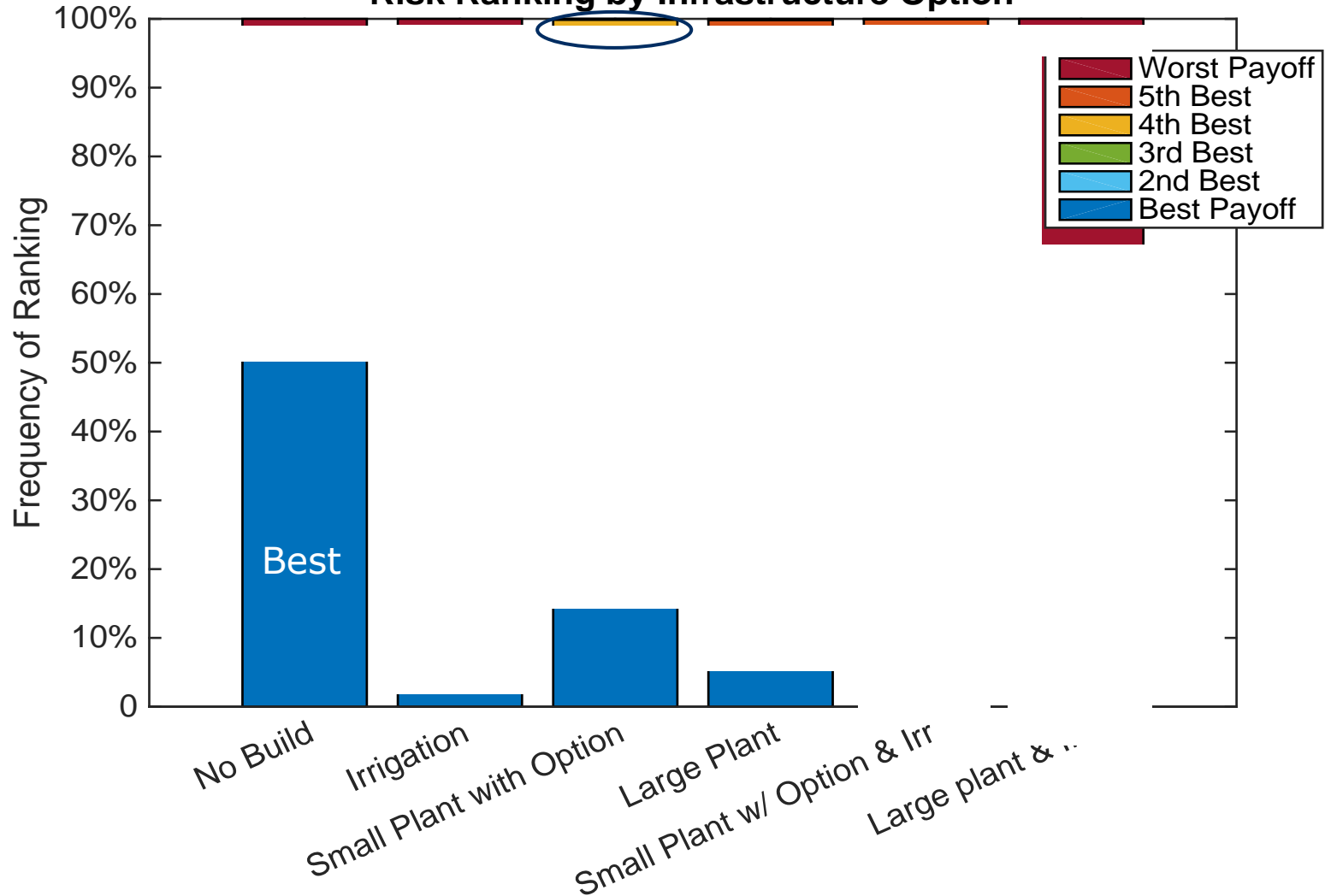


3. Risk Profile



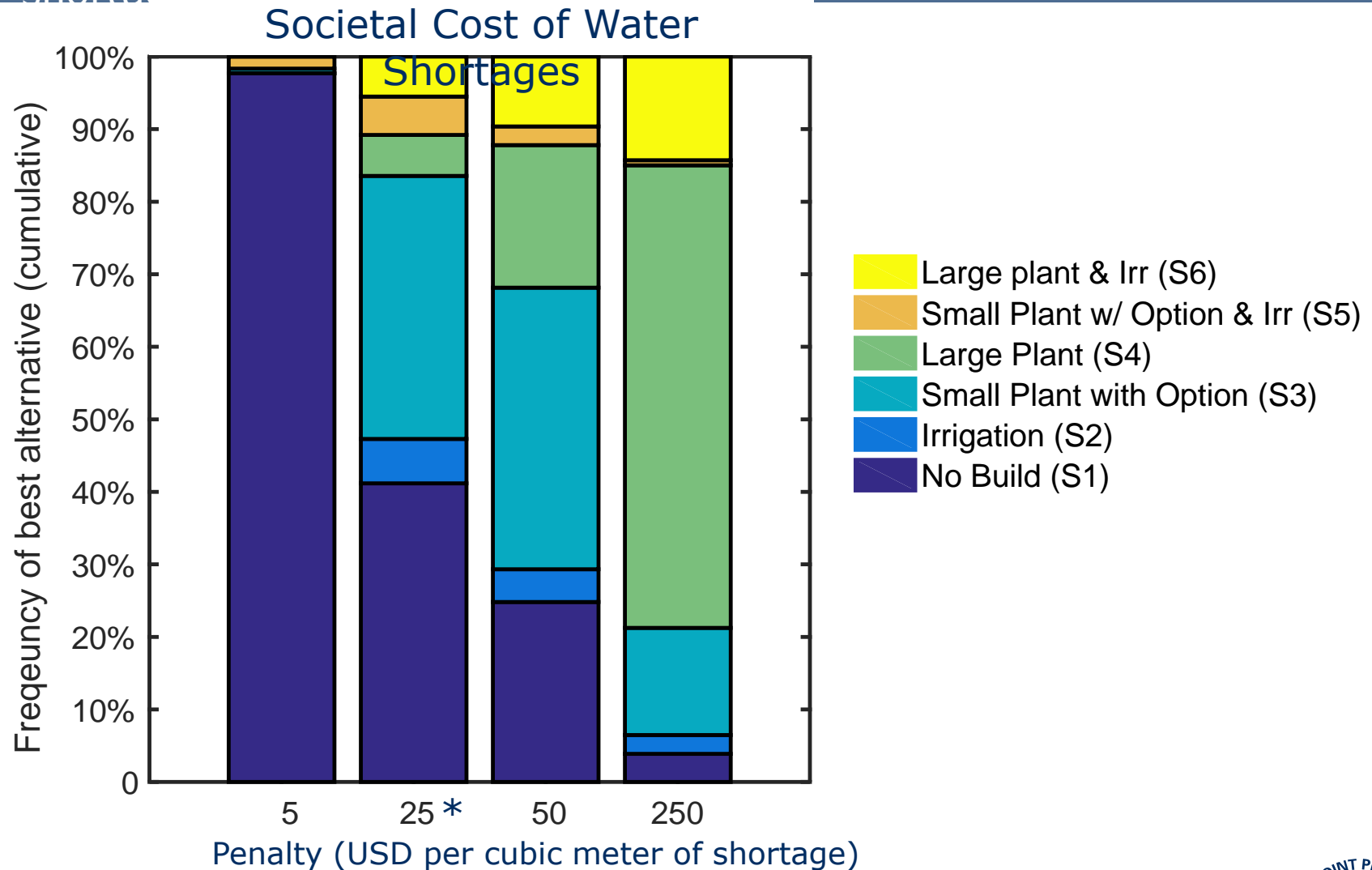
Another way to look at the problem: Choice may depends on desire to avoid bad outcomes

Risk Ranking by Infrastructure Option



Fletcher et al., 2017, J of Water Res. Plan. Man.

Example: Water Supply investment options in Melbourne depend strongly on assumptions social cost of water(i.e. value of water shortage)



Fletcher et al., 2017, J of Water Res. Plan. Man.

Thank You

<http://globalchange.mit.edu>

